KINEMATIC AND KINETIC COMPARISONS BETWEEN ELITE FEMALE AND MALE BASEBALL PITCHERS

by

Yung-Chien Chu

(Under the Direction of Kathy Simpson)

ABSTRACT

The purpose of the current study was to identify the biomechanical features of elite female baseball pitching, and compared to males. Results suggested that females are kinematically similar to males, with significant but limited differences such as an open stride foot placement and the lower knee extension angular velocity. Females had similar timing of kinematics but longer time spent, and much lower loads at shoulder and elbow joints. Ball velocity was lower in females. Females are fully capable of pitching, and the risks of injury like ligament tears are minimal comparing to males according to kinetic results. Females should therefore be encouraged to participate in baseball as pitchers, providing pitch counts are monitored.

INDEX WORDS: Baseball, Pitching, Kinematic, Kinetic, Female, Gender Difference, UCL injury, Force, Torque, Pitch Count, Joint Load

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DEDICATION

I would like to dedicate this work to you,

Poca (a.k.a., A-po, Po-Po, etc.), 1988 - May 11, 2005,

for your 17 years accompanied me.

No matter I was happy or looked melancholy, you were always by my side.

Without you I might not be living until now,

and now I live with your share.

I would never forget the day I picked you,
and the wound you bit me when you were a puppy (in fact, I enjoyed it).
I would never forget your soft white and light-brown fur, your big triangular ears,
your clear, shining eyes, your windmill-wagging tail, and your high standard of food;
your short tongue that always spatters your papaya milk everywhere when you drink,
your never-pissed-off temper, even when Doggy was trying to have your meal,
your never-turned-over pride, your no-licking policy (so bad you taught Doggy doing so),
your warm heart, your tenderness, your elegant posture of crossing your arms,
your insistence of sitting one step above me on stairs like a noble queen,
your ecstasy when you went out to walk me instead of being walked……

For all the time we cherished, Poca,
may you rest in peace, my princess forever.

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Of course, I would even not able to have the chance to conduct this study without two people's kindly help. Mr. Jim Glennie, President of American Women's Baseball League, and Mr. Tom Giffen, President of Roy Hobb's Baseball. Mr. Glennie forward my request of conducting the study to Mr. Giffen once he acknowledged his event sponsors might not allow me to videotape his Women's World Series; Mr. Giffen then generously allowed me to collect data in his Roy Hobb's World Series Women's Division, and provided all possible support with his great staff (and a delicious Mexican dinner!)

That one high-speed camera was damaged in flight security check when I returned from Florida and the delayed IRB application process made me not able to videotape male's data. Dr. Glenn Fleisig, Smith + Nephew Chair of Research of the American Sports Medicine Institute (ASMI), kindly authorized me to use the raw data from his probably the largest males pitching database in the country. Some files were missing, though, and Dr. Rafael Escamilla, associate professor of California State University, Sacramento, found those missing data for me. Their help completed my research, or it would only be a descriptive study of female pitching. Dr. Fleisig also gave me the chance to work at the ASMI as a student researcher. It is my proud and pleasure to work with him at his leading institute in baseball biomechanics. I also want to thank his ex-staff, Jeremy Loftice, a biomechanist and previous collegiate pitcher. Although we only worked together for a short period of time, he gave me lots of insight in analyzing baseball pitching, which is so important for me to interpret my data.

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CHAPTER 1

INTRODUCTION

Even before the first official rules were compiled by Alexander Cartwright in 1845, baseball has been one of the most popular sports in the United States and is considered the America's national pastime. Traditionally, for more than a hundred years of its history, however, baseball has been considered primarily a male sport.

Many people may be surprised to know that females have participated in baseball for almost as long as the history of baseball itself. According to Berlage (1994), the first documented amateur female baseball team can be traced to 1867 at Vassar College. Ironically, the first male professional team, The Cincinnati Red Stockings, was founded two years later in 1869, and only six years before the first paid female baseball game took place in 1875.

Although there is a long history of participation, most females, with the exception of a few girls who are young enough to play in Little League, have had no or limited opportunity to play baseball. To most people, female baseball has only been played during the era shown in the movie, "A League of Their Own." This movie was loosely based on the lives of a team of players in the All-American Girls Professional Baseball League (AAGPBL), which existed from 1943 to

1954. After this time, female baseball then returned to amateur status, and with little media attention, became obscure to the public, and thus lost its popularity for 40 years.

In 1994 another attempt to professionalize female baseball occurred when an independent female professional baseball team, the Colorado Silver Bullets, was founded. The team played against existing male professional and amateur baseball teams, but operated for only three seasons. It was then financially stranded in early 1998, unable to find a sponsor.

However, at present, female baseball is beginning to flourish again. According to The National Federation of State High School Associations, there were 1,382 high school girls participating in varsity girl's baseball in 94 programs in the United States, in the 2005-06 school year ("2005-06 High School Athletics Participation Survey," 2006). More and more teams and leagues, although all amateur, have been and continue to be founded in the United States. They play a short regular season locally; many of the best teams gather annually to play in several national championship series. Moreover, in 2001, The Women's International Baseball Association (formed in 2000) hosted the first international female baseball tournament, the Women's World Series, which then continues to be held annually.

In addition, since 2004, there is a biennial Women's World Cup championship hosted by the International Baseball Federation (IBAF). The IBAF is the body that regulates international baseball competitions in the world, and the Women's World Cup is the first official international female baseball tournament approved by them. As the IBAF has started to promote female baseball internationally, the participation of females in baseball is expected to increase significantly throughout the world. The number of teams participating in the Women's World Cup increased from five in 2004 to seven in 2006 ("Women's Baseball World Cup," 2006).

In regard to pitching, during the early years (1943-1947) of the AAGPBL, the pitching-related rules were most closely resembled those of softball rather than baseball. Compared to the men's baseball game at that time, the women used a shorter pitching distance from pitcher's mound to home plate, larger balls, and underhand pitching. The rules of the AAGPBL continually changed toward the official baseball rules, with overhand throwing adopted in 1948, and the use of the men's size baseball and 60 feet pitching distance made in 1954 (interestingly, also the last year of the league's existence) (Berlage, 1994).

Some female pitchers have competed in male baseball games throughout America baseball history. In 1898, Lizzie Arlington became the first female to play in minor league baseball and threw the historical first pitch against male players. In 1931, 17-year-old pitcher Jackie Mitchell, a minor league pitcher, struck out the all-time legend Babe Ruth and Lou Gehrig in an exhibition game against the New York Yankees (Berlage, 1994). The first win by a female pitcher in official male professional games, however, did not occur until 1998, when Ila Borders created the historical moment in the independent Northern League.

It is evident that as the number of participants and competitive opportunities continue to rise, the demand for evidence-based knowledge to improve performance, minimize injury, and to develop training methods specific to females is needed. However, although much research exists about the mechanics of male baseball, very little is known about the mechanics of baseball as performed by females.

Among all of the defensive positions in baseball, the pitcher is the most crucial one. Baseball pitching is also one of the most rapid human motions ever documented (Fleisig, Barrentine, Escamilla, & Andrews, 1996). The peak shoulder external rotation angular velocity of elite male pitchers has been reported to be greater than 6,000 $^{\circ}\bullet s^{-1}$, and the net centrifugal force of the throwing arm (which requires tissues about the glenohumeral joint to produce equivalent centripetal forces to hold the upper arm into the joint) can be higher than 1,000 N (approximately 224.53 pounds) (Fleisig, Barrentine et al., 1996). Further, this high-demanding motion is executed repeatedly during competitions. For example, a starting pitcher throws about 100 pitches in a typical outing. Hence, it is no surprise that high repetition of such demanding motions is related to increased risk of injury (Lyman, Fleisig, Andrews, & Osinski, 2002). Moreover, there are a variety of pitching motion patterns used that place different levels of loads on involved joints. Inappropriate pitching motions may also be related to higher risk of injury.

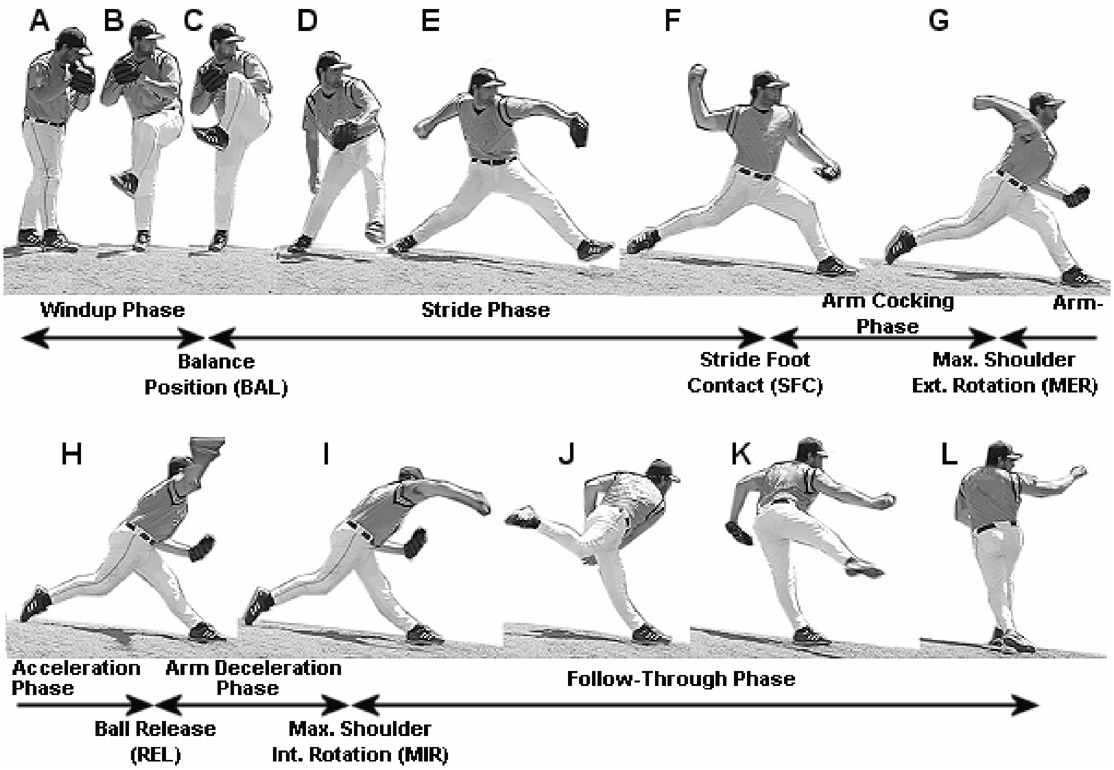


Figure 1.1. The critical events and phases in baseball pitching motion

To understand why I believe that females compared to male pitching will demonstrate some similarities as well as important differences for pitching techniques and loads acting on the shoulder and elbow joints first requires knowing what the basic, overhand-pitching technique involves. According to Fleisig (1994), baseball pitching is divided into six phases separated by five critical events (Figure 1.1). The six phases are windup, stride, arm cocking, arm acceleration, arm deceleration, and follow-through. The five critical events are balance position, stride foot contact, maximum shoulder external rotation, ball release, and maximum shoulder internal rotation (Fleisig, Barrentine et al., 1996). See the section below, “Definitions of Critical Events, Phases, and Other Definitions” for a more in-depth explanation of the phases and critical events; and Table 1.1 and 1.2 for their abbreviated names, respectively.

For male pitchers, application of biomechanical concepts (e.g., generation and transfer of mechanical energy) has been used to understand not only pitching techniques and motions (kinematics) and the causes of movement (kinetics), but also how to exploit the underlying mechanics to improve performance. In combination with tissue biomechanics (e.g., role of fatigue in reducing tissue strength), an understanding of the mechanics of pitching injury also is emerging. Therefore, an understanding of female pitching biomechanics is necessary to understand how skilled female pitchers maximize pitching effectiveness and minimize injury. From these results, we may begin to establish what techniques are appropriate for and specific to women.

While there is a body of published biomechanical research in baseball pitching, almost all of them utilized male pitchers as their participants. Until now, to my knowledge, there exists only one biomechanical study focused on female baseball pitchers, and it is, as of yet, unpublished (Ito, Nakazato, Watarai, & Nakajima, 2005), and contains limited information. This study was an important step, but had several design limitations, the most crucial being the lack of variables. Little interpretation can be made when only two biomechanical variables (kinematic) were reported. Thus, the current study is among the first to describe accurately both the kinematic and kinetic characteristics of female baseball pitching and identify characteristics unique to female pitching.

The Purpose of the Study

The main purpose of the current study was to identify the biomechanical features of fastball pitches performed by skilled female pitchers at a national-level baseball competition to understand how effective pitching is accomplished, and to identify the net joint loads that place stresses on the tissue of the shoulder and elbow.

Secondary, to identify potential characteristics that vary between females and males during pitching, the findings of the current study was compared, albeit cautiously and judiciously, to male data from a comparable male baseball pitching sample, selectively drawn from a previously published research (Escamilla, Fleisig, Zheng, Barrentine, & Andrews, 2001) but completely regenerated using the methods reported in this current study.

The Significance of the Study

Based on the results of the sizeable body of biomechanical research that exists for male baseball pitchers, efforts to improve coaching, training, performance and safety of male pitchers have been made for some time. Especially important is the goal of reducing the potential for debilitating injury to young pitchers. For example, in August 2006, the Little League just adopted an improved pitch-count policy based on emerging evidence of the correlation between arm injuries and pitching when the arm is fatigued ("Regulation and Rule Changes for 2007," 2006). However, there is no such research to guide women pitchers, their coaches, and league coordinators.

Generally speaking, physiological (e.g., muscle mass) and anatomical features (e.g., arm lengths) affecting pitching vary among genders for adults. Thus, it is possible that skilled, female baseball pitchers may have developed techniques that are effective, but different from equivalent male pitchers. Understanding skilled, female pitching technique and muscle kinetics will ultimately lead to more appropriate training and coaching for female pitchers.

Different mechanics among male and female pitchers may also produce different histories of mechanical loading of tissues that are susceptible to chronic overloading at high magnitudes. Therefore, for developing appropriate injury prevention strategies for female pitchers, the results of this study will be an initial step in understanding the loads acting on the pitcher’s arm.

The current study is significant as it is expected to be the first published study to fill this gap in knowledge. If the findings of this study suggest characteristics unique to female pitching, it is hoped that these outcomes will stimulate further investigation leading to recommendations for best training and coaching for females desiring to become skilled pitchers.

Definition of Critical Events, Phases, and Other Terms

For convenience, some abbreviations are used to refer to critical events and phases (Table 1.1) in baseball pitching. For the picture of these critical events and phases, please refer to Figure 1.1.

Table 1.1. Abbreviations and Definitions of Critical Events and Phases

Critical Events	Abbreviation	Description of Events
Balance position	BAL	Stride knee reaches maximum height.
Stride foot contact	SFC	Stride foot touches the ground.
Max shoulder external rotation	MER	Throwing shoulder at max external rotation
Ball release	REL	Ball leaves the throwing hand
Max shoulder internal rotation	MIR	Throwing shoulder at min external rotation

Phase	Abbreviation	Definition
Windup phase	WU-phase	From the initiation of motion to BAL
Mechanical Purpose: Lift the stride leg to store potential energy.		
Stride phase	ST-phase	From BAL to SFC
Mechanical Purposes: Shift the body weight forward to the stride leg, create body forward momentum, and create upper torso/pelvis separation to store elastic energy.		
Arm cocking phase	COC-phase	From SFC to MER
Mechanical Purpose: Sequentially rotate pelvis and upper torso to transfer energy upward to throwing arm.		
Arm acceleration phase	ACC-phase	From MER to REL
Mechanical Purpose: Accelerate the throwing arm and launch the ball at maximal and controllable velocity with optimal spin in correct direction.		
Arm deceleration phase	DEC-phase	From REL to MIR
Mechanical Purpose: Decelerate the throwing arm		
Follow-through phase	FOL-phase	From MIR to the termination of motion
Mechanical Purpose: Land the support leg and regain the body balance.		

Some other terms that are used in the current study are listed here with their definitions:

Kinematics: The branch of mechanics that describes motion of a system in space and time.

Kinetic: The branch of mechanics that describes the action of forces and torques on a system.

Non-throwing arm: The arm the pitcher does not use to throw the ball.

Throwing arm: The arm that the pitcher uses to throw the ball.

Stride leg: The leg that the pitcher steps onto during the stride phase and supports the body during the rest of the pitch. This leg is contralateral to the throwing arm side.

Support leg: The leg that the pitcher stands on during the windup and stride phase. This leg is ipsilateral to the throwing arm side.

"Open" or "closed" orientation: When refer to upper torso, pelvis, or stride foot orientation (Figure 3.5 and 3.7), an "open" orientation means a positive angle, and "closed" indicates a negative angle, relative to a line drawn from the pitching rubber to the home place (i.e., the global X direction). When refer to stride foot placement (Figure 3.7), "open" and "closed" indicate positive and negative placement relative to the global X direction.

Pelvis: A virtual segment whose orientation is aligned between two hip markers.

Upper torso: A virtual segment whose orientation is aligned between two shoulder markers.

The Hypotheses of the Study

In general, it was surmised that female baseball pitchers would display different kinematics and produce different kinetics compared to their male counterparts. Purported gender differences for physiology, morphology, and anthropometrics were assumed to influence on pitching kinematics and kinetics. Compared to males, in general, females generally have smaller body size and muscle mass, less body height and weight, shorter limbs, and decreased absolute muscle strength (Wells, 1991). Therefore, females generally generate less muscle torque and power, and the development of maximum muscle force output occurs later (Riegger-Krugh & LeVeau, 2002). These potential morphological and physiological differences underlie the following hypotheses and their mechanical justifications.

Hypothesis #1: female pitchers were expected to display *lower magnitudes of peaks net joint forces and torques at throwing shoulder and elbow*

It is known that even with very similar kinematics, male pitchers with smaller body size and muscle strength had less joint load during pitching than males with greater body size and strength (Fleisig, Barrentine, Zheng, Escamilla, & Andrews, 1999). Although the kinematics of females was hypothesized different to males, there was no specific reason to assume females had certain kinematics characteristics that increases the joint load. In contrast, several hypotheses presented, such as earlier open of trunk and less trunk rotation, were found related to less joint loads (Wight, Richards, & Hall, 2004).

Hypothesis #2: at stride foot contact (SFC), female pitchers, compared to males, were expected to exhibit:

A) *shorter stride length relative to the body height*

B) *more open upper torso and pelvis orientation angles*

C) *smaller upper torso/pelvis separation angle*

D) *more open stride foot placement and orientation*

With less muscle strength at the support leg, females may not push off of their stride leg with as much force as males do during the ST-phase. Consequently, females should have shorter stride length measure at the SFC. Also, females might not generate as much torque to initiate rapid pelvis rotation from lower body at the end of ST-phase. To compensate, females might start to rotate the pelvis earlier. The pelvis orientation angle at the SFC, therefore, could be more open. With earlier pelvis rotation, the upper torso would also start to rotate earlier, and its orientation should be also more open at the SFC.

Moreover, a slower rotating pelvis creates less inertial lag phenomenon; therefore allowing the upper torso rotation to catch up. Thus, females might not exhibit as large separation angle between the upper torso and pelvis. With the whole trunk rotates earlier and being more open, the stride foot placement and orientation were also expected more open in females.

Hypothesis #3: at maximum shoulder external rotation (MER), female pitchers were expected to exhibit *less maximum shoulder external rotation angle.*

Documenting the value of this angle and comparing between genders is important due to its potential correlation to performance in ball velocity and shoulder tissue strain (Fleisig, Barrentine et al., 1996). Shoulder external during pitching occurs due to the inertial lag phenomenon, caused by the rapid rotation of upper torso. Females were expected to have lower upper torso angular velocity due to less muscle strength of trunk rotators such as abdominal oblique, and the less moment of inertia of forearm vertical to its longitudinal axis to resist initial rotation. Both the two factors are disadvantageous to females to create the inertial lag, the cause of shoulder external rotation.

Hypothesis #4: At the ball release (REL), female pitchers were expected to exhibit *less trunk forward and lateral tilt, greater stride knee flexion angle, and less stride knee extension angular velocity*.

Trunk forward tilt and stride knee extension facilitate each other, as the rectus femoris can serve as both a hip flexor and knee extensor. With less muscle strength, it was reasonable to hypothesize that females have both less peak trunk forward tilt and stride knee extension angular velocity. Moreover, the forward momentum of the body can also facilitate the trunk forward tilt, as the stride foot anchored on the ground after the SFC to stop the forward movement of the body (Matsuo, Escamilla, Fleisig, Barrentine, & Andrews, 2001) , transforming the forward and vertical linear momentum into the rotational momentum of the trunk (MacWilliams, Choi, Perezous, Chao, & McFarland, 1998). Females were not expected to have as much forward momentum to utilize as males, as females have not only less body mass but also less strength to generate linear velocity during the ST-phase.

With expected less upper torso/pelvis separation angle at the SFC, the elastic energy stored in non-throwing side abdominal oblique should be less; with less stretch, the room for contract of this muscle should be also less. Consequently, abdominal oblique can be utilized less in females, showed as lower trunk lateral tilt.

Hypothesis #5:

A) *the relative temporal pattern of females would not be different to males*

B) *the absolute time used to pitch a ball should be longer for females*

That is, the occurrence of peak kinematic measures in relative time series during pitching was the same between genders. However, the absolute time from the stride foot contact to ball release was expected to be longer in females, as females generate less muscle torque and peak the maximum muscle output slower (Riegger-Krugh & LeVeau, 2002).

Hypothesis#6: *overall, females were expected to exhibit less ball velocity*

Kinematic hypotheses above are disadvantageous to females to generate high ball velocities. Open foot placement and orientation decrease the utilization of lower body; open pelvis and upper torso allow less room of trunk rotation; less shoulder external rotation decreases the room of internal rotation; and less stride knee extension and trunk forward tilt transferred less energy up.

Kinetically, females were predicted to produce less angular acceleration. With smaller body sizes, females have less moment of inertia, the ability of an object to resist the effects of an external torque in changing the object's rotational state, and therefore should be beneficial for rapid rotational movements, according to Newton's Law of Acceleration. However, the gender differences in net torque generated, beneficial to males, were expected to be large enough to more than offset the differences in inertial properties. Longer time spent expected for females seems beneficial to females in developing angular velocity; however, this advantage may not offset the described difference in angular accelerations.

Moreover, the linear velocity of hand at ball release decides ball velocity. As linear velocity of a point on a rotating object is equal to the angular velocity of the rotating object multiplied by the distance between the point and the axis of rotation (i.e., the radius of rotation), even if the angular accelerations are comparable between genders, females are still under disadvantage of shorter upper arm and forearm length. The overall outcome would result in less ball velocity for females compared to males.

CHAPTER 2

LITERATURE REVIEW

In this chapter, the results of previous studies regarding baseball pitching will be presented in two major sections. In the first section, the definition of overhand baseball pitching is provided and compared to other pitch-types. Next, the historical findings and approaches to biomechanical investigations of the mechanics of baseball pitching from 1970s to the present are described and categorized. Then, the mechanics of baseball pitching are explained, followed by the exploration of the relationships among pitching skill, ball velocity, kinematic, kinetic, and temporal variables.

Gender-related literature is provided in the second section. First, based on the few limited studies that exist, findings of gender differences for throwing mechanics are presented. Then, gender differences for physiological and anatomical factors that may underlie potential differences of pitching mechanics between females and males are explained.

What is Overhand Baseball Pitching?

Baseball pitching is a specific form of throwing prescribed and regulated in the eighth chapter of baseball rules (*2007 Official Rules of Major League Baseball*, 2006). Traditionally, it is categorized into four subtypes: overhand, three-quarter, sidearm, and underhand.

These subtypes are classified by the position of the throwing arm at ball release. When you are standing on home plate as a hitter facing the pitcher’s mound, if the pitcher’s throwing arm is approximately horizontal at the instant of ball release, the pitcher is throwing sidearm. If the throwing arm is higher than horizontal, it is three-quarter to overhand. If the throwing arm is lower that horizontal, it is underhand.

It was believed that the different arm positions were caused entirely by varying the lateral tilt angle of the trunk, as the shoulder abduction angle at ball release for all pitch types was approximately 90° (Atwater, 1970). This observation, however, was not entirely correct. Although the different arm positions could be mainly attributed to lateral trunk tilt, Matsuo, Takada, Matsumoto, and Saito (2000) found that sidearm and underarm pitchers had smaller shoulder abduction angles than overhand and three-quarter style pitchers.

It is difficult, even for professional baseball coaches, to classify some pitchers who throw with a style that is somewhere between an overhand and a three-quarter style (Matsuo et al., 2000). Also, it does not really make sense to divide all throwing styles with a ball release position above the horizontal line into two categories, as people do not apply the same categorization to underhand delivery styles. Thus, in this study, the term “overhand” pitching includes both overhand and three-quarter delivery described before. Under this definition, overhand, sometimes also called overarm or overhead, is the most common method of baseball pitching (Braatz & Gogia, 1987), and is the focus of most previous literatures and this study.

The Historical Development of Pitching Analysis Methodology

Although human throwing has been studied since early twentieth century, baseball pitching started to get researchers' attention in the 1960s, resulting in reports of basic, descriptive kinematics. For example, among the few studies published during that decade, Logan, McKinney, Rowe and Lumpe (1966) reported that the average ball velocity of 21 varsity baseball team candidates was 33.8 $m{\bullet}s^{-1}$. However, limited technology, cost and enormous amounts of time required to complete a study using high-speed 35 mm film restricted the number, scope and validity of studies (Shapiro, 1978).

Thus, although the understanding of the biomechanics of locomotion was proceeding rapidly during this time, pitching mechanics did not. As the sagittal plane is the primary plane of lower extremity motions during walking, 2-D studies were relatively simpler and financially more feasible to accomplish. In contrast, the path of the throwing arm in baseball pitching moves primarily in diagonal planes as well as substantially in all three anatomical planes. Therefore, the mechanics of baseball pitching has to be described in three dimensions. However, it was very, very difficult for researchers during that time to measure human body movement three-dimensionally. Established methods of that time either involved cumbersome methodology that not only cost considerable time and money but sometimes wasn’t precise enough (Shapiro, 1978). For example, at present, six to eight optoelectronic cameras are often the minimum for capturing the spatial locations of a large number of reflective markers to reconstruct the positions and motions of the entire body. Complex computer algorithms can accurately track the locations of the markers in real-time. In contrast, for example, Atwater (1970), one of the pioneers of contemporary throwing biomechanics, measured overhand softball throwing for 26 men and women. She set three 35 mm high-speed film cameras perpendicular to each other, capturing views of the participant from the rear, side, and overhead. To track the locations of various joints required biomechanists to use a film projector to project the film images from a given frame onto a surface, then hand digitize each coordinate of every joint from every frame of film from every camera. Furthermore, during this pre-desktop computer era, computations were difficult to perform. In her recommendation for further study, the techniques used to obtain joint kinematic data were described as rather difficult and needed improvement. (Atwater, 1970)

The computational difficulties were not been solved until a method to reconstruct 3-D coordinates in space from several 2-D camera views for photography, i.e., direct linear transformation (DLT), was presented in 1971 by Abdel-Aziz and Karara. The accuracy of DLT was then evaluated as suitable for use with high-speed cinematography and appeared to be superior in flexibility to other 3-D cinematographic methods developed in 1970s (Shapiro, 1978).

DLT has then continued to be widely used to measure three-dimensional human body movements, including baseball pitching.

Since 1980s, DLT has been applied in almost all biomechanics studies regarding baseball-pitching techniques. Although their 3-D reconstruction methods were not reported clearly, Pappas, Zawacki, and Sullivan (1985) calculated the average shoulder external velocity as 6180°•s^{-1} among 15 Major League baseball pitchers. This study may be the first published kinematic study of baseball pitching. Several other noted pitching researchers, Elliott, Grove, Gibson, and Thurston (1986) and Feltner and Dapena (1986) used DLT to obtain kinematic data of baseball pitching.

Electromyography (EMG) analysis also has been utilized as another important approach to understand baseball-pitching techniques. Ball velocity is achieved by a series of well coordinated body movements, through which energy and momentum are transferred (Fleisig, Barrentine et al., 1996). Thus, investigating muscle activation patterns using EMG has served to understand the coordinative actions of muscles involved in pitching. The first EMG study of baseball pitching in the United States was published in early 1980s (Jobe, Tibone, Perry, & Moynes, 1983), approximately 12 years after the earliest studies were completed in Japan (Kazai et al., 1976; Toyoshima, Matsui, & Miyashita, 1971). Combined with high-speed cinematography, from the results of the relative EMG magnitudes and the timing of when these muscles were activated, the major muscles used during pitching were identified and an understanding of the contributions of these muscles to the production of pitching movements was furthered (Jobe, Moynes, Tibone, & Perry, 1984; Jobe et al., 1983; Sisto, Jobe, Moynes, & Antonelli, 1987).

The Phases and Critical Events in Baseball Pitching

Jobe et al. (1983), provided one of the earliest, completed the descriptions of baseball pitching motion. The movement was divided into four phases: windup, cocking, acceleration, and follow-through. The cocking phase was divided into two sub-phases: early and late cocking. To clarify, the early cocking sub-phase was then called stride phase, and the late cocking sub-phase, therefore, retained the name, “arm cocking phase.” Feltner (1989) called the arm acceleration phase the “release phase”. In addition, an initial part of the follow-through phases was later identified as an independent phase, named, “arm deceleration” (Dillman, Fleisig, & Andrews, 1993; Werner, Fleisig, Dillman, & Andrews, 1993).

Some researchers had different opinions about the naming and definition of phases. For example, some thought the stance the pitcher assumed before the windup began was a phase independent from the windup phase (Braatz & Gogia, 1987). Some divided the arm cocking phase into early and late preparatory phases (Feltner, 1989), some considered the windup, propulsion (stride), and late cocking as sub-phases of an overarching “cocking phase” (Pappas et al., 1985). Most recent studies, including the current one, use the six-phase description consisting of windup, stride, arm cocking, arm acceleration, arm deceleration, and follow-through (Figure 1.1). The details of the six-phase kinematic description are presented below.

Phase 1: Windup (WU-phase)

The first phase, windup, begins when the pitcher initiates the motion, and ends when the maximum height of the stride knee is reached (Fleisig, Barrentine et al., 1996) or when the ball leaves the gloved hand (Braatz & Gogia, 1987; Dillman et al., 1993). These two events may not happen simultaneously, or even in a fixed order among, among pitchers. This phase has been reported to last between 0.5 to 1.3 sec (Braatz & Gogia, 1987). The main purpose of this phase is to put the pitcher in a good starting position for increasing the kinetic energy of the body that can then be transferred to the ball (Fleisig, Barrentine et al., 1996; Pappas et al., 1985). Other reported purposes include setting the rhythm of the pitching motions, concealing the ball and the pitcher’s grip, and distracting the batters (Pappas et al., 1985).

Baseball rules require that the support foot touch the rubber (the strip of rubber parallel to home base that lies on the top of the pitcher’s mound) at the initiation of the pitching motion. Although some pitchers may stand at approximately 45° relative to the rubber for better balance (Braatz & Gogia, 1987), most pitchers start their motion from a standing position directly facing the batter. Then, by stepping backward with the stride foot and shifting their body weight onto this foot, their support foot is turned out lateral and placed in front of the rubber (Dillman et al., 1993).

The WU-phase is initiated when the weight starts to be shifted forward from the stride foot to the support foot (i.e., the body's center of mass starts to move anteriorly). The weight shift between the feet in a short period of time is believed to set the rhythm for the delivery of the pitch (Dillman et al., 1993).

It was described that as the WU-phase is initiated, the entire trunk rotates around 90º toward the right with the longitudinal axis of the support leg as the axis of rotation (Braatz & Gogia, 1987), and the stride leg is lifted upwards by hip flexion with the knee flexed. However, more recently, pitchers have been observed to rotate their trunk more than 90º (Stodden, Fleisig, McLean, Lyman, & Andrews, 2001). Stodden et al. reported that the upper torso orientation is -30±13° at the end of WU-phase. This means that the upper torso rotates 120° if starting from a stance position in which the trunk faces the home plate. The pelvis orientation was also reported -36±13° at the end of WU-phase moment.

During the WU-phase, the support leg remains in a slightly flexed position (Fleisig, Barrentine et al., 1996). Lifting the stride leg stores potential energy; subsequently, will be transferred into kinetic energy that contributes to moving the body forward during the stride phase. When the knee of the stride leg reaches its maximum height, the whole body should be in a balanced position at which the entire body is motionless. At this instant, the stride leg and the whole body are ready to start moving toward the target (i.e., home plate).

Kinematic data about this phase are limited. An average angle (±SD) of 117.0±2.8º of stride hip flexion, a 16.5±7.5º shank flexion angle relative to vertical, and an average of 33.1±4.1 cm of height of stride knee above the stride hip at balance position were reported for six pitchers on the Australian National Team roster (Elliott et al., 1986). It is evident that this is a limited sample and generalizable only to Australian pitchers of this era.

Phase 2: Stride (ST-phase)

The ST-phase begins when the stride leg begins to move toward the target and the arms separate from each other, and ends when the stride foot contacts (SFC) the ground (Fleisig, Barrentine et al., 1996). In this phase, the body weight is transferred forward, creating body momentum. The trunk rotates and stretches to store elastic energy. The throwing arm moves to a ready position to pitch. And the stride leg lands firmly, providing a solid basis to support and facilitate the pitching motion in following phases.

The stride leg moves downward and forward simultaneously by hip extension and hip abduction. The support foot remains planted on the ground and the ankle joint plantar-flexes when the body's COM shifts forward (Elliott et al., 1986). The support hip abducts to push downward and backward against the pitching rubber, thereby causing the body to move forward.

The forward linear velocity of the pelvis was reported to be 2.1±0.4 m•s^{-1} (Matsuo et al., 2001). The gluteus maximus of the support side is heavily involved in this movement, and was found moderately to highly activated (Watkins et al., 1989). the stride hip also rotates externally and the support hip rotates internally and extends (Fleisig, Barrentine et al., 1996). The gluteus maximus of the stride side is also moderately activated (Watkins et al., 1989).

During the early ST-phase, the support knee is flexed (Elliott, Grove, & Gibson, 1988), and then extends (Elliott et al., 1988), simultaneously when internal rotation of the femur about the hip joint occurs during the late ST-phase. The stride knee usually extends during early stride from the balance position, and will then flex with the increase of stride hip external rotation, to prepare for contacting the ground. These motions of lower extremities also helps the pelvis initiate the rotation toward the stride leg (Braatz & Gogia, 1987), after having rotated more than 90º in the opposite direction during the preceding WU-phase (Stodden et al., 2001).

At the end of the balance position, the upper torso and the pelvis are aligned similarly in a closed position (Stodden et al., 2001). Then, both segments start to rotate toward the stride leg in the ST-phase, but the pelvis rotates faster than the upper torso (Braatz & Gogia, 1987). Therefore, the rotation of the upper torso continues to lag behind lower torso (Stodden et al., 2001). This causes abdominal oblique and rectus abdominis stretched, causing elastic energy to be stored in these muscles (Fleisig, Barrentine et al., 1996). The greatest difference between the orientation of the upper torso and the pelvis reached the peak of 51º occurred just prior to the SFC event (Ishida & Hirano, 2004). According to Braatz and Gogia (1987), the lumbar spine appears to flex during the late WU-phase and moves into hyperextension during the late ST-phase. The trunk also was observed qualitatively to slightly tilt toward non-throwing side. However, these observations could not be quantified.

The motions of the upper extremities are properly synchronized with the body and the lower extremities, and are considered to be among the most important aspects of pitching (Dillman et al., 1993). During the ST-phase, the throwing shoulder rotates externally, but the non-throwing shoulder may rotate externally or internally, depending on personal preferences. Both arms are abducted and horizontally abducted to stretch the pectoralis major. The deltoid, the supraspinatus, the infraspinatus, and the teres minor were also reported highly activated during this phase (Jobe et al., 1983). These purpose of these movements is suspected to be the storage of elastic energy for utilization during subsequent phases (Fleisig, Barrentine et al., 1996).

The throwing elbow, which was flexed during the WU-phase, may remain flexed through the ST-phase. Some pitchers, however, may demonstrate elbow extension during early ST-phase and then flexion during the late ST-phase. The throwing wrist moves from a position of slight flexion to one of hyperextension (Fleisig, Barrentine et al., 1996). The brachioradialis, the major wrist and finger extensors, and the pronator teres activate moderately to bring the throwing arm and hand up (Sisto et al., 1987). The kinematics variables reported during the ST-phase were still extremely limited.

Stride Foot Contact (SFC)

For pitching analysis, the SFC is the first moment that kinematics are calculated thoroughly to provide a picture in detail. Kinematic variables at this moment, especially those regarding lower body, reveal how the stride was done and decide how the throwing can be performed.

For example, the stride length, defined as the distance either between the rubber and the ankle of the stride foot, or between the ankles, is considered as an important factor of successful pitching. According to Dillman et al. (1993), a stride that is too long may hamper the rotation of hips and legs, while a shortened stride is not long enough to stretch out the body. Therefore, either error would reduce the ball velocity. The location of the stride foot is also essential to pitching. If the stride foot is placed too closed, the rotation of hips would be limited, and the lower body could not contribute to pitching much. However, if the foot is placed too open, the hips would rotate too early, and the energy from the hips could not be utilized due to improper timing (Dillman et al., 1993).

For reference, the previously reported kinematic variables at the instant of SFC are presented in Table 2.1 to 2.3.

Table 2.1. Previously Reported Kinematic Variables Regarding the Lower Body at the Stride Foot Contact

Study	Participants	Stride Knee Flexion (º)	Stride Foot Placement (m)	Stride Length (%BH)	Stride Orientation (º)
Escamilla et al. (1998)	College	48±11	0.00±0.10	(84±5)	-8±12
Dillman et al. (1993)	College, Pro		0.004±0.08	75±4, (87±5)	-15±10
Elliott et al. (1986)	AUS National	48	0.07±0.01	(82.3±2.3)	
Fleisig et al. (1999)	Youth	43±12		(85±8)	
	HS	50±9		(85±9)	
	College	48±12		(85±6)	
	Pro	46±8		(86±5)	
Fleisig, Zheng et al. (1996)	HS, College	51±11		74±5	
Fleisig, Escamilla, Andrews et al. (1996)	College	47±10		71±4	
Hirano (1985)	JPN Pro			75.1	
	JPN Youth			72.5	
Escamilla et al. (2002)	Pro	49±4		(91±8)	
	KOR Pro	50±8		(85±5)	
Matsuo et al. (2001)	College, Pro			(87.3±6.4)	
	College			(86.3±4.9)	
Fleisig et al. (2006)	College	38±9	-0.19±0.14	70±4	-19±11
Stodden et al. (2001, 2005)	HS to Pro	49±6			
Dun et al. (2007)	Pro	38.5±11.4	-0.22±0.14	82.5±4.1	
	Pro	43.8±7.4	-0.22±6.1	77.3±5.1	

Note. Values in parentheses represent stride length computed as the distance between the front edge of pitching rubber and the ankle of stride foot, instead of the distance between the ankles.

Table 2.2. Previously Reported Kinematic Variables Regarding the Trunk at the Stride Foot Contact

Study	Participants	Upper Torso Orientation (º)	Pelvis Orientation (º)	UT / Pelvis Separation (º)
Stodden et al. (2001, 2005)	HS to Pro	-19±15	27±13	
Ishida & Hirano (2004)	JPN College	6±15	50±7	
Dun et al. (2007)	Pro	-13.0±9.4	37.2±12.3	50.0±8.9
	Pro	-24.0±7.4	23.5±6.1	47.0±8.5

Table 2.3. Previously Reported Kinematic Variables Regarding the Throwing Arm at the Stride Foot Contact

Study	Participants	Shoulder Abduction (°)	Shoulder Horizontal Abduction (°)	Shoulder External Rotation (°)	Elbow Flexion (°)
Escamilla et al. (1998)	College	98±12	20±10	52±33	84±17
Dillman et al. (1993)	College, Pro	About 100	About 30	53	
Feltner & Dapena (1986)	College		18	46	63
Fleisig et al. (1999)	Youth			67±28	74±17
	HS			64±25	82±17
				55±29	85±18
				58±26	87±15
Fleisig, Zheng et al. (1996)	HS, College	93±12	17±12	67±24	98±18
Fleisig, Escamilla, Andrews et al. (1996)	College			42±26	90±18
Pappas et al. (1985)	Pro	About 90	About 30	90-120	
Feltner (1989)	College	76±9	18±7	45±44	63±23
Sakurai et al. (1993)	JPN College	82.9±12.0	20.4±8.1	106.0±21.5	107.1±19.9
Escamilla et al. (2002)	Pro	88±8	27±10	45±19	89±12
	KOR Pro	104±7	14±9	68±17	96±18
Fleisig et al. (2006)	College			46±25	86±16
Stodden et al. (2001, 2005)	HS to Pro	96±14	17±12	63±32	96±20
Ishida & Hirano (2004)	JPN College	78±9	23±15	72±34	105±18
Werner et al. (2002)	Pro	109±33			
Dun et al. (2007)	Pro			47.7±33.0	94.6±23.1
	Pro			47.5±32.0	89.4±8.7

Phase 3: Arm Cocking (COC-phase)

Arm cocking, the third phase of baseball pitching, starts from the SFC, and ends at when the throwing shoulder reaches its maximum external rotation (MER). As described, the SFC was the zero point in time frame of pitching analysis in most biomechanical studies, and the moment of ball release (REL) was taken as the end point. This period of time takes around 0.15 sec, and the

COC-phase occupies around 80% of it. Previously reported kinematic variables during this phase are shown in Table 2.4.

Table 2.4. Previously Reported Kinematic Variables during the Arm Cocking Phase

Study	Participants	Upper Torso Max Angular Vel. (°•s^{-1})	Pelvis Max Angular Vel. (°•s^{-1})
Escamilla et al. (1998)	College	1220±100	640±80
Fleisig et al. (1999)	Youth	1180±110	650±110
	HS	1130±110	640±90
	College	1190±110	670±90
	Pro	1200±80	620±80
Fleisig, Zheng et al. (1996)	HS, College	1170±100	660±80
Fleisig, Escamilla, Andrews et al. (1996)	College	1170±80	620±70
Escamilla et al. (2002)	Pro	1248±73	673±48
	KOR Pro	1212±76	611±51
Matsuo et al. (2001)	College, Pro	1227±72	637±88
	College	1179±104	633±74
Fleisig et al. (2006)	College	1120±90	600±110
Ishida & Hirano (2004)	JPN College	1040±90	490±80
Dun et al. (2007)	Pro	1098.8±70.0	535.3±79.8
	Pro	1143.2±125.5	592.3±83.2

During the COC-phase, a sequential movement from lower body through the trunk to the throwing shoulder generated a kinetic chain, and has the throwing arm ready to accelerate explosively in the next phase. The pelvis keeps rotating, and its angular velocity increases. The upper torso starts to rotate following the rotation of the pelvis. This delay twists the trunk, and makes the upper torso kept extending through this phase. The twist was found highly related to ball velocity (r^2=0.69). With such twist, elastic energy is therefore stored, and stretch reflex is induced (Ishida & Hirano, 2004).

The pelvis rotates at the fastest velocity about 30~40% of the pitching period between the SFC and the REL, while the upper torso achieves its fastest rotation at nearly 50% of the period. The angular velocity of the upper torso is around twice of the pelvis angular velocity. The abdominal oblique of the non-throwing side of the trunk was observed highly activated in this phase, twisting the upper torso toward the non-throwing side rapidly (Watkins et al., 1989).

Dillman et al. (1993) indicated that in highly skilled pitchers, the upper torso hyperextended as the upper torso rotated around to face the home plate, which is just around the end of the phase. However, the hyperextension has not been quantified due to technical difficulties, and can be only observed visually. With the hyperextension, the rectus abdominus and the lumbar paraspinus were observed highly activated at the non-throwing side, and moderately activated at the throwing side (Watkins et al., 1989).

The sequential rotation of the pelvis and the upper torso facilitates the external rotation of the throwing shoulder through this phase, and making the shoulder horizontally abducts in early this phase. With these rotational motions, the rotator cuff (subscapularis, supraspinatus, infraspinatus, and teres minor) are highly activated during this phase to stabilize the glenohumeral joint, reported by Jobe et al. (1983). It was reported no forward movement of the ball during this phase (Pappas et al., 1985), but in fact, the ball still moves forward a little, especially in early this phase.

The horizontally abducted throwing shoulder then starts to horizontally adduct slightly. The maximum horizontal adduction is achieved at around 60%~75% of this phase. The pectoris major and the latissimis dorsi are highly activated accompanied by the shoulder horizontal adduction. The serratus anterior is also highly activated to provide a stable glenoid platform (Jobe et al., 1984).

The throwing elbow keeps flexing in most of the COC-phase, and reaches its maximum flexion angle of approximately 100º just before the MER, and starts to extend nearly the end of this phase, to reduce the moment of inertia that resists the shoulder internal rotation (Fleisig, Barrentine et al., 1996). The biceps are moderately activated during this period, and the triceps are then highly activated to initiate elbow extension for acceleration (Jobe et al., 1984). The triceps also controls the elbow flexion via eccentric contraction. It was known that if the triceps is paralyzed, the elbow would keep flexing toward its anatomical limit (Fleisig, Barrentine et al., 1996).

The non-throwing shoulder, abducted since the ST-phase through early COC-phase, adducts and horizontally abducts with the rotation of the trunk, and the non-throwing elbow flexes. The glove is moved to just in front of the shoulder, the left chest, or next to the left thigh, depending on personal preference.

The initial abduction of the non-throwing arm increases the moment of inertia of the upper torso along the longitudinal axis, holding the upper torso from rotating together with the pelvis, creating the twist between the upper torso and the pelvis. The shoulder adduction and elbow flexion motions in late arm cocking move the non-throwing arm closed to the body, decrease the moment of inertia of the body mainly on transverse plane, and therefore increase the angular velocity of the upper torso rotation (Ishida & Hirano, 2004). The non-throwing arm will then virtually stay at the same position relative to the trunk until the end of pitching motion.

Maximum Shoulder External Rotation (MER)

At the instant of MER, the throwing shoulder is about 10º horizontally adducted. The shoulder abduction angle varies from 80 to more than 100º. The external rotation angle of the throwing shoulder is around 180º (Table 2.5). But it should be noticed that this angle is a measurement of true glenohumeral rotation combined with some scapulothoracic motion and spine hyperextention (Fleisig, Barrentine et al., 1996). In some studies involving the measurement of passive glenohumeral range of motion of elite baseball pitchers and tennis players, the maximum shoulder external rotation values were only between 100 to 140º, depending on different measurement and manipulation methods (Borsa, Dover, Wilk, & Reinold, 2006; Borsa et al., 2005; Mullaney, McHugh, Donofrio, & Nicholas, 2005). Thus, the extremely shoulder external rotation might be attributed to rapid rotational movement of upper torso, while inertial lag of the forearm drag behind the body.

Table 2.5. Previously Reported Kinematic Variables at the Shoulder Maximum External Rotation

Study	Participants	Shoulder Abduction (º)	Shoulder Horizontal Abduction (º)	Shoulder External Rotation (º)	Elbow Flexion (º)
Escamilla et al. (1998)	College			171±6	
Dillman et al. (1993)	College, Pro			178	
Feltner & Dapena (1986)	College	102	11	170	74
Fleisig et al. (1999)	Youth			177±12	
	HS			174±9	
	College			173±10	
	Pro			175±11	
Fleisig, Zheng et al. (1996)	HS, College			173±10	
Fleisig, Escamilla, Andrews et al. (1996)	College			172±12	
Pappas et al. (1985)	Pro			160	
Werner et al. (1993)	Pro			185	85
Feltner (1989)	College	102±8	10±6	169±10	
Sakurai et al. (1993)	JPN College	84.9±6.7	11.2±11.7	181.3±7.0	94.5±13.4
Escamilla et al. (2002)	Pro			181±8	
	KOR Pro			167±8	
Matsuo et al. (2001)	College, Pro			179.0±7.7	
	College			166.3±9.0	
Fleisig et al. (2006)	College			178±7	
Stodden et al. (2001, 2005)	HS to Pro			173±11	
Ishida & Hirano (2004)	JPN College	101±8	5±13	182±12	89±13
Dun et al. (2007)	Pro			182.6±4.3	
	Pro			172.8±6.4	

According to Newton’s Law of Inertia (rotationally), the magnitude of torque applied to an object, e.g., upper arm, must be sufficient to overcome the rotational inertia of the object to cause rotation. For non-rigid objects, e.g., human body, when torque is applied to an object, not all of the object will start to rotate simultaneously; some parts will “lag behind.” For example, when the upper torso starts to rotate, the upper arm and the forearm are “at rest” relative to the upper torso, and will not rotate until the torque applied to that arm is sufficient to overcome its rotational inertia; therefore, the shoulder external rotation is created.

Phase 4: Arm Acceleration (ACC-phase)

The forth phase starts at the MER, and ends at the instant of ball release (REL). This phase is very short, occupying only 20% of the 0.15 second whole pitching period. In this phase, the pelvis angular velocity decreases much, transferring the angular momentum up to the upper torso, which keeps rotating rapidly (Stodden et al., 2001). These rotational motions and the forward trunk tilt move the throwing shoulder even more forward. The spine that hyperextended during the COC-phase starts to flex in this phase, and will reach nearly neutral position at the REL (Fleisig, Barrentine et al., 1996). The rectus abdominus, lumbar paraspinatus, abdominal oblique, and gluteus maximus were all highly activated in this phase (Watkins et al., 1989).

With the motion of the trunk, the throwing shoulder starts to rotate internally, the throwing elbow extends, and the throwing wrist flexes. The combination of these motions creates a whip-like movement of the throwing arm, additively accelerates each involved segments, and generates the maximum velocity at the end of the whip, the index and middle fingers, and at the ball. Although this series of motions is traditionally described as sequentially initiated from the shoulder, through the elbow, then to the wrist, it is not the case. The elbow extension starts the earliest, just before the shoulder reaches the MER (Fleisig, Barrentine et al., 1996). According to most temporal parameters reported, the elbow also reaches its maximum extension angular velocity earlier, and then the shoulder gets its maximum internal rotation angular velocity. It is interesting that while the elbow reaches the maximum value around 90% plus of the pitching period, the shoulder gets the maximum just prior or slightly after the REL.

Table 2.6. Previously Reported Kinematic Variables during the Arm Acceleration and Deceleration Phase

Study	Participants	Shoulder Max Internal Rotation Ang. Vel. (^{o}•s^{-1})	Elbow Max Extension Ang. Vel. (^{o}•s^{-1})
Escamilla et al. (1998)	College	7550±1110	2440±240
Dillman et al. (1993)	College, Pro	6940±1080	
Elliott et al. (1986)	AUS National		964.7
Feltner & Dapena (1986)	College	6100±1700	2200±400
Fleisig et al. (1999)	Youth	6900±1050	2230±300
	HS	6820±1380	2180±340
	College	7430±1270	2380±300
	Pro	7240±1090	2320±300
Fleisig, Zheng et al. (1996)	HS, College	7550±1360	2340±300
Fleisig, Escamilla, Andrews et al. (1996)	College	7290±1090	2350±250
Pappas et al. (1985)	Pro	6180	4595
Werner et al. (1993)	Pro		2300
Matsuo et al. (2000)	JPN Pro	5149±1539	2696±433
Escamilla et al. (2002)	Pro	7844±954	2565±280
	KOR Pro	8006±1071	2401±251
Matsuo et al. (2001)	College, Pro	7724±1037	2537±247
	College	7350±1283	2353±320
Fleisig et al. (2006)	College	6520±950	2210±260
Ishida & Hirano (2004)	JPN College	5250±840	2240±240
Dun et al. (2007)	Pro	7253.5±1324.1	2375.9±289.4
	Pro	6642.0±668.7	2344.7±160.9

The throwing shoulder adducts, horizontally abducts, and internally rotates in this phase. The abduction angle has been stably maintained at nearly 100º before this phase, and decreases to just above 90º at the REL. The internal rotation during this phase of baseball pitching is one of the most rapid human movements documented, with the angular velocity consistently calculated at over 6,000º per second (Table 2.6). A peak value was reported at 9,198º per second by Pappas et al. (1985). The serratus anterior and the latissimus dorsi are still highly activated, but the pectoralis major is activated moderately (Jobe et al., 1984). The rotator cuff may show high (Fleisig, Barrentine et al., 1996) or limited activation (Jobe et al., 1983).

The elbow extension angular velocity is also high, usually higher than 2000º per second (Table 2.6). Although very high activation of the triceps was found during this phase (Jobe et al., 1984), the triceps may contribute limited amount of this velocity. For example, while some researches found elbow extension torque during this phase (Feltner, 1989; Werner et al., 1993), others found elbow flexion torque (Fleisig, Andrews, Dillman, & Escamilla, 1995; Fleisig, Escamilla, Andrews et al., 1996). For more evidences, it was also reported that a pitcher could throw a ball at more that 80% of his maximum speed after his triceps was paralyzed, according to a review article by Flesig, Barrentine et al. (1996). Moreover, Toyoshima et al. (1973) also found that using maximum voluntary effort of the triceps could generate only half of the elbow extension angular velocity in throwing, comparing to a throwing motion that involves the whole body. It seems that the elbow extension velocity generated during this phase is largely due to the rapid rotation of hips, trunk, and shoulder (Fleisig, Barrentine et al., 1996), but the efforts made by elbow extensors also can not be overlooked.

Due to the limitation of camera resolution, the kinematic data of wrist during pitching are extremely rare. The reflective markers have to be small enough to be attached at the wrist and not to interfere the pitching, but such size was hardly identified with most high-speed cameras. The only reported wrist kinematic data are by Sakurai et al. (Sakurai, Ikegami, Okamoto, Yabe, & Toyoshima, 1993), who put three sticks on their participants' wrist and hand to measure the wrist angles during pitching, but this approach might affect and alter the pitching mechanics. Most studies modeled the hand and the ball as the summation of their mass at the position of the wrist marker. Recently, the improvement of camera resolution makes it possible to put small reflective markers on wrist hand and still detectable. The modeling has therefore changed that the mass of the hand and the ball could be move to a correct position instead of at the wrist (Stodden, Fleisig, Langendorfer, & Andrews, 2006b). Although the new technology has helped the refinement of the kinetic analysis, additional wrist kinematic data has yet provided.

The wrist flexion is the triggered much later, about 20 ms prior to the REL, and the forearm pronation occurs around 10 ms before the REL (Pappas et al., 1985). Dillman et al. (1993) suggested that the forearm pronation observed may actually be the combined effect of elbow extension and shoulder internal rotation, but the pronator teres was noted moderately activating during this phase (Sisto et al., 1987). The wrist flexes for almost 20º from a hyperextended position to almost neutral, between the MER to the REL. Jobe et al. (1984) indicate that the hand just traveled with the ball together and did not provide further acceleration to before the REL by wrist flexion. Some EMG evidence showing low activation level of the wrist flexors might support this (Sisto et al., 1987; Werner et al., 1993), but other research reported high activation of the wrist flexors (Fleisig, Barrentine et al., 1996). This has not been verified due to limited kinematic and unavailable kinetic data. The flexion angular velocity of the wrist has not been reported, too.

Ball Release (REL)

Serving as the last check point of kinematics, the REL contains important information relative to ball velocity, such the stride knee extension angular velocity and the trunk forward tilt angle. For example, pitchers may or may not extend their stride knee at this instant, but the knee extension at this instant was found a trait of pitchers with higher ball velocity (Matsuo et al., 2001). The details of these variables and their relationship to ball velocity are discussed in later sections. Previously reported values are presented in Table 2.7 to 2.9.

Table 2.7. Previously Reported Kinematic Variables Regarding the Lower Body at the Ball Release

Study	Participants	Stride Knee Flexion (º)	Stride Knee Extension Ang. Vel. (º•s^{-1})
Escamilla et al. (1998)	College	46±13	
Fleisig et al. (1999)	Youth	36±11	
	HS	43±13	
	College	39±13	
	Pro	38±13	
Fleisig, Zheng et al. (1996)	HS, College	40±12	
Fleisig, Escamilla, Andrews et al. (1996)	College	36±12	
Escamilla et al. (2002)	Pro	32±9	
	KOR Pro	48±14	
Matsuo et al. (2001)	College, Pro		243±149
	College		124±141
Dun et al. (2007)	Pro	27.8±12.5	
	Pro	39.9±13.7	

Table 2.8. Previously Reported Kinematic Variables Regarding the Trunk at the Ball Release

Study	Participants	Trunk Forward Tilt (º)	Trunk Lateral Tilt (º)
Escamilla et al. (1998)	College	28±5	28±9
Fleisig et al. (1999)	Youth	32±9	
	HS	31±9	
	College	33±10	
	Pro	33±9	
Fleisig 96	HS, College	32±10	34±9
Fleisig 96b	College	31±8	
Matsuo et al. (2000)	JPN Pro		24±5
Escamilla et al. (2002)	Pro	36±7	22±12
	KOR Pro	26±8	25±7
Matsuo et al. (2001)	College, Pro	36.7±6.7	
	College	28.6±11.1	
Fleisig et al. (2006)	College	33±7	23±9
Stodden et al. (2001, 2005)	HS to Pro	32±9	27±12
Dun et al. (2007)	Pro	36.8±4.2	17.9±6.1
	Pro	28.7±7.2	22.9±10.2
Ishida & Hirano (2004)	JPN College		

Table 2.9. Previously Reported Kinematic Variables Regarding the Throwing Arm at the Ball Release

Study	Participants	Shoulder Abduction (°)	Shoulder Horizontal Abduction (°)	Shoulder External Rotation (°)	Elbow Flexion (°)
Escamilla et al. (1998)	College		10±9		35±2
Dillman et al. (1993)	College, Pro	About 95	About 0	105	
Feltner & Dapena (1986)	College	92	2	113	20
Elliott et al. (1986)	AUS National				36.0±2.6
Fleisig et al. (1999)	Youth		11±9		24±7
	HS		10±8		23±7
	College		9±9		23±6
	Pro		9±10		23±5
Fleisig, Zheng et al. (1996)	HS, College		7±7		22±6
Fleisig, Escamilla, Andrews et al. (1996)	College		9±10		25±7
Pappas et al. (1985)	Pro	90±10			25
Werner et al. (1993)	Pro				20
Feltner (1989)	College	79.3±10.2	6.0±6.9		35.3±12.2
Sakurai et al. (1993)	JPN College			132.6±23.1	
Escamilla et al. (2002)	Pro		8±8		21±5
	KOR Pro		5±6		20±5
Fleisig et al. (2006)	College	96±9	12±8		29±6
Stodden et al. (2001, 2005)	HS to Pro		12±9		27±10
Ishida & Hirano (2004)	JPN College	102±6	6±10	104±12	24±5

Phase 5: Arm Deceleration (DEC-phase)

The arm deceleration phase starts from the REL to the throwing shoulder reaches its maximum internal rotation (MIR). The elbow continues to extend and the shoulder keeps rotating internally after the ball released, and several muscles are highly activated to slow down the arm movement. The peak shoulder internal rotation angular velocity is reached just before or after the REL, and will decrease to zero at the end of this phase. The MIR occurs approximately the shoulder internally rotates to the neutral position (Dillman et al., 1993), but there have been no kinematic numbers during this phase or at this moment reported.

The left hip flexes, the stride knee keeps extending, and the trunk forward tilt angle keeps increasing. The rectus abdominus, lumbar paraspinatus, abdominal oblique, and gluteus maximus are moderately activated in this phase (Watkins et al., 1989). The throwing shoulder continually adducts and horizontally abducts after the REL, and then turn to abduct and horizontally adduct through out this phase. The shoulder abduction angle increases to over 100º at the MIR. The throwing arm moves across the body toward the left hip with continuing upper torso rotation and left hip flexion. This cross-body motion is considered important to minimize the irritation of the rotator cuff (Braatz & Gogia, 1987). The throwing elbow starts to flex from the minimum flexion angle of approximately 20º just after the REL, to nearly 40º just prior to MIR (Escamilla, Fleisig, Barrentine, Zheng, & Andrews, 1998).

EMG analysis indicated that the deltoid and the rotator cuff, quiet during the ACC-phase, are all highly activated in the arm deceleration phase (Jobe et al., 1983). These muscles generate posterior and inferior force to resist anterior and superior humeral translation, stabilizing the glenohumeral joint (Fleisig, Barrentine et al., 1996). The biceps and the brachialis are moderately activated to decelerate the elbow extension (Fleisig, Barrentine et al., 1996; Sisto et al., 1987).

The wrist and finger extensors are moderately or highly activated to decelerate the flexing wrist and fingers (Fleisig, Barrentine et al., 1996; Sisto et al., 1987; Werner et al., 1993).

Phase 6: Follow-through (FOL-phase)

The FOL-phase is from the MIR to the moment that the pitcher lands the support leg on the ground. A good follow-through can not directly improve the throw, but is critical in minimizing the risk of injury (Dillman et al., 1993). In this phase, the throwing elbow extends, the throwing shoulder keeps horizontally adducting but starts to adduct again, and the throwing forearm supinates. The shoulder external rotation angle increases. The throwing arm travels a long arc of deceleration. The trunk keeps flexing, and the stride knee should keep extending (Dillman et al., 1993). Such a kinetic chain allow energy to be absorbed by the large muscles of the trunk and legs, reducing the stress placed on the throwing arm (Fleisig, Barrentine et al., 1996). The deceleration process is continuing in this phase, but the joint forces and torques generated are generally lower than during this arm deceleration phase (Fleisig, Barrentine et al., 1996).

Findings Regarding Baseball Pitching from Kinetic and GRF Analysis

While the methodology of 3-D kinematic analysis of baseball pitching was well developed, researchers also started to apply inverse dynamics method to their kinematic findings to obtain the net joint load data during baseball pitching. Feltner and Dapena (1986) published the first known study regarding the kinetics of maximal effort pitching. Their application of the inverse dynamics method to calculate the kinetic variables has been widely used by other following researchers, such as Fleisig and his research team.

Along with kinetic data, the magnitudes, directions and timing of when these forces are applied to each foot by the ground, i.e., ground reaction forces (GRF), are also helpful to further understand the contributions of the lower body during baseball pitching. The importance of lower extremities in baseball pitching should not be minimized (Pappas et al., 1985), as the lower body initiates the pitching motion and is the origin of the kinetic chain. However, the GRF studies regarding baseball pitching are limited. Elliott et al. (1988) used one force platform to record the GRF patterns of eight national class pitchers from Japan, Taiwan, and Australia, but only one camera was used. The first published research combining dual-feet GRF measurement and 3-D cinematography, to my knowledge, is McWilliams et al. (1998). Unfortunately, the movements of the body were not reported, so understanding the effects of GRF on pitching effectiveness could not be elucidated.

It was reported low forces, torques, and muscle activity are generated in the throwing arm during the WU-phase (Fleisig, Barrentine et al., 1996). The muscles surround the throwing shoulder had minimal activity (Jobe et al., 1983), and the muscles across the throwing elbow also showed relative low activities (Sisto et al., 1987).

The vertical ground reaction force exerted by the support foot during the ST-phase was reported nearly 0.9 BW (body weight) at balance position, dropped to 0.8 BW when ball left the glove, then increased to the peak value of 1.2 BW just prior the SFC, and dropped again to 1.0 BW at the SFC, according to Elliott et al. (1988). In contrast, the same force reported by McWilliams et al. (1998) was initially around 1.0 BW and dropped to around 0.65 BW at the SFC.

As the total vertical force would equal to body weight if the pitcher was not moving, the vertical force exerted by the stride foot had increased to around 0.3 BW in McWillams et al. (1998), the difference of vertical force at the SFC between the two studies could be due to differences in the definitions of SFC between the two research groups; that is, McWilliams et al. took a later time point that part of the weight had transferred to the stride foot. This also happened in other studies (Escamilla et al., 1998), as there is no absolute criterion to decide the happening of the SFC.

Elliott et al. (1988) also reported the horizontal push-off force exerted by the support foot gradually increased from nearly zero (at balance position) to 0.6 BW prior to the SFC, and dropped to 0.55 BW at the SFC. McWilliams et al. (1998) reported a similar pattern but much smaller magnitude, which was from 0.2 BW to 0.35 BW, then dropping back to around 0.2 BW at the SFC.

During the COC-phase, the trunk continually moves forward, and the body weight shifts to the stride foot from the support foot. The resultant GRF exerted by the support foot dropped from more than 0.9 BW to 0.7 BW in only 0.04 sec after the SFC (Elliott et al., 1988), while the resultant GRF of the stride foot increased through this phase and reaches around 1.5 BW (MacWilliams et al., 1998).

These important findings elucidated the role of the stride leg and foot played in this phase. The stride foot anchors the body in anterior-posterior (AP) direction (MacWilliams et al., 1998). The stride knee has initial flexion after the SFC to absorb the impact of landing, and the quadriceps contracts eccentrically to decelerate this knee flexion (Fleisig, Barrentine et al., 1996). A knee flexion angle that is less than 90º should be maintained. The quadriceps should then isometrically contract to stabilize the stride leg (Fleisig, Barrentine et al., 1996). The gluteus maximus of both sides were all highly activated (Watkins et al., 1989).

After the stride leg is stabilized, the stride knee will start extending to exert an anterior force toward the ground. The inferior force applied by the stride foot on the ground also increases with such a knee extension motion, accompanied by the weight shifting toward the stride foot. The support foot, therefore, leaves the ground and will not land until the current pitching motion is finished. The anterior and inferior components of the resultant GRF kept increasing through this phase, according to MacWilliams et al. (1998). By applying such forces to the ground, the stride leg stops the forward movement of the lower body after the SFC, “bracing” the upper torso to tilt forward more rapidly. In medial-lateral (ML) direction, a medially directed GRF is applied to stop the rotation of the stride foot just after the SFC. The magnitude was about 0.1 BW (MacWilliams et al., 1998).

The COC-phase is also the start of kinetic analysis in previous researches. During this phase, the maximum proximal force applied by the humerus on the shoulder of the throwing arm could be over 600 N just before the MER and keeps increasing. Each of the anterior or superior force could be over 300 N prior to the MER. The horizontal adduction and internal rotation torque also reaches their maximum prior to the MER. The elbow varus torque reaches is maximum during this phase, and the highest average value reported was 120 Nm (Werner et al., 1993).

The stride knee keeps extending during the ACC-phase, exerting more forces against the ground to facilitate the forward tilt of the trunk and to hold the body stable (Fleisig, Barrentine et al., 1996). Such a strong support from lower body is considered a factor of successful pitching. If the stride knee flexes and moving forward, the forward trunk tilt may be hindered (Fleisig, Barrentine et al., 1996). The AP component of GRF reached a maximum of 0.72BW just before the REL, while the vertical component also reached a maximum of 1.5BW at the same moment. (MacWilliams et al., 1998). In the ML direction, the GRF changes to lateral, as the stride foot applied a medial force to stabilize the body, against the laterally momentum caused by the rapid rotation of the body and the throwing arm. The magnitude was nearly 0.1BW (MacWilliams et al., 1998). The shoulder and elbow compressive force keeps increasing during this phase, and will reach the maximum just after the REL.

Table 2.10. Previously Reported Kinetic Variables

Study	Participants	Elbow Proximal Force (N)	Shoulder Proximal Force (N)	Elbow Varus Torque (Nm)	Shoulder Internal Rotation Torque (Nm)
Feltner & Dapena (1986)	College	830±80	860±120	100±20	90±20
Fleisig et al. (1995)	College, Pro	900±100	1090±110	64±12	67±11
Fleisig et al. (1999)	Youth	400±100	480±100	28±7	30±7
	HS	630±140	750±170	48±13	51±13
	College	770±120	910±130	55±12	58±12
	Pro	910±140	1070±190	64±15	68±15
Fleisig, Zheng et al. (1996)	HS, College	710±110	850±140	51±10	54±10
Fleisig, Escamilla, Andrews et al. (1996)	College	800±90	910±110	54±7	55±10
Werner et al. (1993)	Pro	780		120	
Matsuo et al. (2000)	JPN Pro	(112±12)	(114±18)	(1.3±0.7)	
Escamilla et al. (2002)	Pro	(111.7±13.3)	(134.5±17.2)	(3.9±0.7)	(4.1±0.7)
	KOR Pro	(93.0±11.1)	(107.7±14.4)	(3.4±0.3)	(3.7±0.5)
Fleisig et al. (2006)	College	988±110	1056±157	82±13	84±13
Stodden et al. (2005)	HS to Pro			(4.6±0.8)	(4.6±0.8)

[a] Parenthesized numbers were normalized values. For forces, it was normalized to body weight; for torques, it was normalized to the product of body weight and body height.

It was estimated that the deceleration forces were twice the acceleration forces (Braatz & Gogia, 1987). This estimation was not correct, but the deceleration phase is indeed very demanding. An average maximum shoulder compressive force of 1090 N, which occurs just after the REL, was once reported (Fleisig et al., 1995), and other studies provided similar values. The maximum elbow compressive force, also occurs around the REL, was also reported an average value of 900 N (Fleisig et al., 1995). In some studies that reported relative value of force, these two forces were normalized, and were over or near the body weight of the pitchers. The shoulder adduction torque and horizontal abduction torque also reach their peak value in this phase. Previously reported kinetic values are presented in Table 2.10.

Ball Velocity as a Performance Evaluation Tool

On a pitch-by-pitch basis, for a pitcher, to throw a strike in which the batter cannot accurately hit is considered success. To achieve this success using a fastball, a pitcher may maximize the ball velocity to shorten the time the batter could react, control the pitch accurately through a location that the batter hard to attack, and manage the tailing movement of the pitch letting the batter hard to track. However, accuracy and movement are hard to quantify for evaluation; therefore, ball velocity is one variable suitable for evaluate pitching performance, as it can be objectively and easily measured. Atwater (1970) even defined maximum ball velocity as her operational definition of throwing skill when she grouped her participants during a maximum effort softball throwing experiment. This definition has been used by many investigators.

Furthermore, velocity magnitudes appear to be related to competitive league skill level. The average maximum ball velocities were found significantly different among pitchers from different competition levels of playing (Matsuo et al., 2001; Murata, 2001). Ball velocities progressively increase from youth, high school, and college, to professional (Fleisig et al., 1999). Pitchers divided into unskilled rather than the skilled groups by coaches' evaluations showed significantly lower ball velocities (Iwase & Murata, 2001; Murata, 2001). Such relationships established the connection between the definitions of pitching skill in motor learning and in real playing.

Another reason to use ball velocity as a measure of performance is that the magnitude is reasonably consistent within pitchers. It was found remarkably consistent for each pitcher (Feltner & Dapena, 1986; Pappas et al., 1985), with typically 3% of variation among same type pitches. Such consistency was expected as the pitching level and specialization skills increase (Escamilla et al., 1998). Additionally, pitchers in higher competition level have accumulated more practice and experience in their career, as described in the definition of skill. The fact that healthy, professional male pitchers at 30 years-old had ball velocities similar to their 20-year old colleagues (Dun, Flesig, Loftice, Kingsley, & Andrews, 2007) indicates that ball velocity is learned and has a relatively permanent nature. Therefore, ball velocity is, although not perfect, an acceptable index to evaluate pitching performance level within a group. And there have been many previous studies focused on finding the relations between ball velocity and biomechanics characteristics.

GRF Comparison

The generation of ball velocity is largely attributed to the rotation of trunk, and the trunk rotation is supported by lower body. Therefore, GRF analysis, which represents the pattern of the forces exerted by the lower body, may contain critical information regarding to the generation of ball velocity.

The purposes of the ST-phase are to transfer the weight forward, release the potential energy stored, and transfer it to kinetic energy. These purposes are partly accomplished by the support leg, producing ground reaction forces (GRF) that are of high enough magnitude, in the correct direction and generated at the right time. Elliott et al. (1988) compared the resultant GRF patterns between the three fastest pitchers and three slowest pitchers among eight participants from Taiwan, Japan, and Australia national teams. They found that pitchers with lower ball velocity began their drive with the support leg earlier than those with higher ball velocity. MacWilliams et al. (1998) then verified this trend. Also, the faster group had their support leg exerting forces thru the ST-phase, while the force exerted by the support leg of the slower group dropped sharply before the SFC. It was concluded that the ability to drive the body over a stabilized stride leg was a characteristic of the faster pitchers (Elliott et al., 1988).

However, the biomechanics underlying the findings of Elliott et al. (1988) are unknown as they reported no kinematic or other. In addition, they selected six participants from eight potential participants to form a fast and a slow pitching group with three participants in each group. This arrangement might have led to low statistical power or to non-generalizable results. Perhaps for these reasons they only performed only a descriptive study, reporting values for single participants. Therefore, the ‘different’ GRF patterns of the two groups may not really represent the ranges of characteristics of fast and slow pitchers. These issues make the results hard to interpret.

MacWilliams et al. (1998) conducted another GRF study ten years after. They found that linear wrist velocity, which was highly correlated to ball velocity (r^2=0.97), was highly correlated to normalized (to BW) support foot push-off force in both A-P direction (r^2=0.82) and vertical direction (r^2=0.74). This supported the Elliott et al.’s conclusion that greater anterior GRF was a characteristic of pitchers throwing at faster ball velocities. Moreover, they used a dual-force plate design and collected the GRF pattern on the stride foot. They found that the linear wrist velocity was also highly correlated to the normalized stride foot landing force in both A-P direction (r^2=0.86) and vertical direction (r^2=0.70). Push-off A-P force was positively related to landing A-P force. This makes sense, because when greater push-off force occurs, the body accelerates forward with greater momentum during the stride, and, thus needs either greater force and/or longer time to generate the GRF necessary to stop the body’s motion after the stride foot contact.

Although reporting no kinematic data to support their interpretations, MacWilliams et al. (1998) also stated that higher vertical landing force indicated that a pitcher stepped down his stride foot onto the mound more forcefully. That is, to exert more force against the ground. They surmised that the stride leg not only stops the forward movement of lower body, but should also “brace up” to transfer the kinetic energy upward to the trunk. In other words, the stride leg acts somewhat like a rigid strut. They recommended that to generate a strong breaking and bracing up force, the stride knee should extend.

Kinematic Comparison: Between-Pitchers Approach

Kinematic analysis could tell more of the relationship between baseball pitching motion and ball velocity. One of the most interesting, and probably the earliest published study focusing on this topic was Matuso et al. (2001). In this study, the researcher measured the ball velocity of 127 college and professional pitchers. Twenty-nine pitchers who had ball velocity 1SD over the average were categorized into the fast group, and 23 pitchers with ball velocity 1SD lower than the average formed the slow group. While 21 pitchers of the 29 in the fast group were professional, all 23 pitchers in the slow group were collegiate. Then a series of kinematic variables were compared between the groups. The average ball velocities of the two groups were significantly different.

Several kinematical differences were found. Pitchers in the fast group had significantly lower stride knee flexion angular velocity than the slow group. The stride knee flexion occurred just after the stride foot contacted the ground, and absorbed some kinetic energy. The fast group and slow group had similar body weight and pelvis linear velocity in the ST-phase, so the kinetic energy generated should be similar. It seemed that the fast group had less kinetic energy absorbed; therefore, the fast group had more energy that could be transferred upward through the kinetic chain, and generate higher ball velocity. The fast group also had significantly higher knee extension angular velocity at the instant of ball release. This result emphasized the effect of “bracing” of the stride leg. As described in the hypotheses section, the stride knee extension also facilitated trunk forward tilt, which was also significantly higher in the fast group.

More interestingly, Matsuo et al. found that most these pitchers’ patterns of knee angle change between the SFC and the REL could be categorized into four types: small initial flexion and rapid later extension, large initial flexion and small later extension, small initial flexion and small later flexion, and continue flexion. Most fast pitchers were categorized into the first type, and the numbers of fast pitchers decreased along the spectrum. There was no fast pitcher in the fourth type. In contrast, slow pitchers were rare in the first type, and equally distributed in the second and third types. Pitchers in the fourth type were rare. It seemed that less energy absorption after the SFC and rapid knee extension prior to the REL were essential to ball velocity, and the later was even more important than the former.

The maximum shoulder external rotation angle was found significantly larger in the fast group. This could be caused by the larger forward trunk tilt angle, creating larger spine hyperextension. The rotation of upper torso could also contribute to it. However, although there was a trend that maximum upper torso angular velocity was higher in the fast group, the difference failed to reach the significance of $p<0.01$ set by the researchers. With larger shoulder external rotation and trunk forward tilt, the time durations during the ACC-phase were almost the same between the two groups; therefore, the fast pitchers had longer arm path to accelerate the ball. The maximum angular velocities of shoulder internal rotation and elbow extension was not significant different, although there was a trend that the fast group had higher value. But the additive effect of the increased angular velocity along the kinetic chain may contribute to the difference in ball velocity between the groups.

In summary, the researchers concluded that fast and slow pitchers had similar arm kinematics, and different trunk and leg movements mainly caused the difference in ball velocity. But the interpretation must be made carefully since the difference in ball velocity could partially explained by the fact that the fast group had higher body height and longer arm length.

Similar results were found when Escamilla et al. compared the professional pitchers from Korea and the United States (Escamilla, Fleisig, Barrentine, Andrews, & Moorman, 2002). While the Korean pitcher had significant slower ball velocity, they also showed less shoulder maximum external rotation at the MER, less trunk forward tilt, and more knee flexion at the REL. Although in this study, the American pitchers also had higher body height and longer arm length, the researchers reported that 10% of the variance of ball velocity between groups could be explained by kinematic differences.

The comparison results described are based on pitchers in different competition or skill level but had similar age, such as college and professional. For pitchers in different age groups, ball velocity may be significantly different while the kinematic are very similar. The difference in ball velocity here is mainly because those pitchers were in different body development stages and therefore had different size and muscle strength. In a research that included youth, high school, college, and professional pitchers, only five of the 15 kinematic variables showed significant difference at least between two groups, and none of them really showed an increase or decrease trend through the increase of developmental levels (Fleisig et al., 1999).

In some Japanese studies, pitchers with above average ball velocities were assigned into the fast group and the rest went into the slow group. Such method was not as good but the difference between the groups still reached significance. These studies provided some interesting findings.

In the ST-phase, the fast group showed more knee flexion on their support foot, and the knee angle was the same between the groups at the SFC (Takahashi, Fujii, & Ae, 2002c), and the support knee extension angular velocity was found positively related to the ball velocity (Takahashi, Fujii, & Ae, 2002b). That is, pitchers in the fast group bent their support knee more and then extended it more rapidly to push the body forward, producing more kinetic energy.

The maximum elbow extension angular velocity was found similar between fast and slow pitchers, but the fast pitchers started to accelerate the elbow later in the ACC-phase (Takahashi, Fujii, & Ae, 2002a). The more rapid acceleration indicated much higher relative elbow extension torque generated. However, the elbow extension torque was never compared in kinetic studies.

Some other results these Japanese studies supported the findings from Matsuo et al. (2001). For example, the initial extension angular velocity of the stride knee was related to the ball velocity. Also, pitchers with faster ball velocity showed significantly faster shoulder horizontal adduction angular velocity near the end of the COC-phase (Takahashi et al., 2002a), while a similar trend although not significant was reported by Matsuo et al.

Evaluation and opinions from coaches were also used to group pitchers into skilled or unskilled (Iwase & Murata, 2001; Murata, 2001), and the ball velocities between groups were still significantly different. These studies found skilled pitcher had better consistency in pitching mechanics, and the non-throwing shoulder showed less normalized movement during the arm cocking and acceleration phases. Such movement was found highly negatively related to ball velocity (r^2=0.80). The results indicated that a nearly fixed non-throwing shoulder provided a pivot point that the upper torso and throwing arm to rotate about. If the non-throwing arm moved to rotate back when the throwing shoulder rotated forward, then the rotation axis shifted toward the spine. Consequently, the torque arm ipsilateral to the throwing arm was shortened, and the angular momentum shared by the contralateral side of trunk increased. Therefore, the ball velocity was reduced.

Kinematic Comparison: Within-Pitcher Approach

However, the between-pitchers approach has its limitation, as the grouping process ignored the individual differences such as muscle strength, flexibility, and neuromuscular coordination (Matsuo, 2001). Also, although the average ball velocity of pitchers in higher skill level was generally higher than it of pitchers in lower skill level, it was not necessarily true that a single pitcher with higher ball velocity was in or had higher skill level than a single pitcher with lower ball velocity. Therefore, some researchers tried to use within-pitcher approach find out the kinematic difference when pitchers varied their ball velocity.

Stodden et al. (2001) focused on the kinematic differences of upper torso and pelvis rotation. They found that at the instant of MER, the more rotation of the pelvis and the upper torso, the higher the ball velocity an individual pitcher could achieve. More rotation of pelvis at the REL was also related to higher ball velocity. Not surprisingly, the average pelvis angular velocity during the COC-phase and the average upper torso angular velocity during the ACC-phase phase were related to ball velocity. This fact also revealed the sequential roles of pelvis and upper torso in consecutive phases, and the upward transfer of angular momentum.

Some other results derived from this study were reported later (Stodden, Fleisig, McLean, & Andrews, 2005). The shoulder horizontal abduction angle was related to a pitcher’s higher ball velocity; since the more horizontal abduction, the more stretch in pectoralis major due to the dragging effect, storing more elastic energy and inducing stretch reflex. The higher horizontal abduction also represented the longer acceleration path available. The trunk forward tilt angle was also significantly related to ball velocity.

Average shoulder abduction angle during ACC-phase was found negatively relative to ball velocity. The reason provided was that the pectoralis major and the latissimus dorsi were highly activated during acceleration, and reduced shoulder abduction. However, a contradictive result was also found that the shoulder abduction angle and ball velocity both decreased with accumulation of pitch count, probably due to fatigue (Barrentine, Takada, Fleisig, Zheng, & Andrews, 1997). Further researches are needed to figure out the relationship between this angle and ball velocity.

It should be noticed that in these two studies, the pitchers were required to vary the ball velocity for at least 1.8 $m \cdot s^{-1}$, which equals to 4 mph. The instruction that slow down a certain velocity from their maximum effort pitch was obviously not familiar to them during practice or games. Moreover, the required variation was quite large, more than 5% of the average velocity of 35$m \cdot s^{-1}$, while the common variance of ball velocity had been reported at 3% (Escamilla et al., 1998). It was therefore quite questionable if the pitchers purposefully altered their pitching mechanics in such setting.

Computer Simulation

Another individual-based approach is computer simulation. Pitching motion is videotaped, kinematic and kinetic variables are calculated, anthropometric information is measured, and these data are adjusted and optimized using a set of optimization equations for different purpose, such as maximizing ball velocity or minimizing net joint load.

To maximize wrist velocity, the optimal angle of shoulder abduction during the arm cocking and acceleration phases was found 93±9.2º, and to minimize elbow varus torque, the optimal angle was 101±19º. The videotaped data showed actual shoulder abduction at 101±13º (Matsuo, Matsumoto, Mochizuki, Takada, & Saito, 2002). It seems pitchers tended to adjust their pitching motion for less joint load instead of pursuing maximum velocity.

The limitation of such approach was that the model could not fully represent the complexity of pitching motion. For example, in Matsuo et al. (2002), a three-link model was used to simulate the throwing arm. However, while the shoulder abduction angle was adjusted, it was quite possible that the kinematic and kinetic of trunk and lower body also altered, and these were not covered in the model. Assumptions such as the trunk and the lower body kept unaltered were made, but it was not known if such assumptions were valid.

Temporal Comparison

The movements of body segments along the kinetic chain are triggered sequentially during baseball pitching. To each pitcher, there are infinite combinations of the trigger timing among these segments; however, only one optimal timing combination that maximizes ball velocity exists.

Computer simulation showed although there were many timings of torques that produced outputs near the maximum, only one timing combination generated maximum velocity (Herring & Chapman, 1992). Due to the limitation of three-segment model described, it is almost impossible to find out the optimal timing combination for one pitcher. But it is reasonable that on group basis, some trends of better timing combination among successful pitchers could be found, by observing the relative time of onset or the peak of kinematic variables. The results of these kinds of temporal analysis, however, are still limited.

In Matsuo et al. (2001), the high velocity group presented their maximum elbow extension and shoulder internal angular velocity significantly earlier than the slow velocity group. There were also trends that the fast group had earlier maximum pelvis and trunk forward tilt angular velocity, although did not reach the significance of $p<0.01$. One interesting thing was the average of maximum forward trunk tilt angular velocity occurred just prior the ball release in the fast group but later than the ball release in the slow group.

Table 2.11. Previously Reported Temporal Variables, Part 1

Study	Participants	Max Pelvis Ang. Vel. (%)	Max Upper Torso Ang. Vel. (%)	Max Trunk Forward Ang. Vel. (%)	Time Expended from SFC to REL (s)
Escamilla et al. (1998)	College				0.149±0.016
Dillman et al. (1993)	College, Pro				
Feltner & Dap (1986)	College				0.183±0.033
Fleisig et al. (1995)	College, Pro				0.139±0.017
Fleisig et al. (1999)	Youth	37±16	49±11		0.150±0.025
	HS	39±20	50±11		0.150±0.020
	College	34±18	51±11		0.145±0.020
	Pro	34±14	52±7		0.145±0.015
Fleisig, Zheng et al. (1996)	HS, College	35±19	50±8	99±16	0.145±0.022
Feltner (1989)	College				0.183±0.033
Sakurai et al. (1993)	JPN College				0.130±0.020
Escamilla et al. (2002)	Pro	34±17	52±7		
	KOR Pro	34±8	49±7		
Matsuo et al. (2001)	College, Pro	27.8±15.9	51.2±6.9	96.0±11.8	
	College	35.3±18.0	52.7±12.1	104.3±21.5	
Fleisig et al. (2006)	College	30±17	50±9	104±2	
Stodden et al. (2001, 2005)	HS to Pro	39±17	52±12	93±20	0.145±0.030
Ishida & Hirano (2004)	JPN College	11.3±21.2	52.3±15.9		0.132±0.028

Although not significant, some trends that supported the finding of Matsuo et al. was found in the study of comparing American and Korean professional pitchers, in which the Americans were evaluated to have higher skill and threw faster. The American pitchers showed earlier occurrence of maximum upper torso angular velocity, elbow extension angular velocity, and shoulder internal rotation angular velocity (Escamilla et al., 2002).

Table 2.12. Previously Reported Temporal Variables, Part 2

Study	Participants	Max Shoulder External Rotation (%)	Max Shoulder Internal Rotation Ang. Vel. (%)	Max Elbow Flexion (%)	Max Elbow Extension Ang. Vel. (%)
Escamilla et al. (1998)	College	82±3		57±17	
Dillman et al. (1993)	College, Pro				
Feltner & Dap (1986)	College	82.5±3.8			
Fleisig et al. (1995)	College, Pro				
Fleisig et al. (1999)	Youth	80±6	103±2		92±3
	HS	81±5	102±3		91±3
	College	81±5	102±5		91±5
	Pro	81±5	102±4		91±4
Fleisig, Zheng et al. (1996)	HS, College	81±4	103±2	53±14	92±3
Feltner (1989)	College	83		45	
Sakurai et al. (1993)	JPN College	73±8.5			
Escamilla et al. (2002)	Pro	80±7	100±8	57±15	90±7
	KOR Pro	84±5	103±2	54±15	93±2
Matsuo et al. (2001)	College, Pro	80.6±5.4	102.3±2.0		91.1±1.9
	College	80.7±4.4	104.4±1.8		93.0±2.4
Fleisig et al. (2006)	College				93±3
Stodden et al. (2001, 2005)	HS to Pro	81±6	104±5		95±11
Ishida & Hirano (2004)	JPN College		100.0±1.5		86.3±1.5

It was also found that pitchers with higher ball velocity reached the peak stride hip adduction angular velocity earlier in the COC-phase (Takahashi et al., 2002a). The stride hip adduction in this phase is in fact achieved by pelvis rotation. Although the pelvis rotates since the balance position, the rotation velocity increases rapidly in the COC-phase. It seems the faster pitchers initiate the rapid pelvis rotation earlier, in agreement with Matsuo et al. (2001).

The slow pitchers were found the pelvis, upper torso, and horizontally adducting shoulder achieved the peak angular velocity almost simultaneously, and the increase of elbow extension angular velocity just occurred immediately. In contrast, the fast pitchers achieved the maximum angular velocities in a sequence of pelvis, upper torso, shoulder horizontal adduction, and elbow extension, with noticeable gap between each consequent motion. It was concluded that fast pitchers appropriately applied sequential movements along the segments along the kinetic chain to maximize ball velocity (Takahashi et al., 2002a).

When comparing the temporal variables among pitchers in different development levels (i.e., different ages), some researchers found that there was no different in the relative time of occurrence of peak values of kinematic variables (Fleisig et al., 1999). On the other hand, other researchers found the higher the development level, the later the onset of trunk rotation after the SFC (Aguinaldo, Buttermore, & Chambers, 2004). If both studies provided valid results, as the peak angular velocity of upper torso and pelvis did not show any increasing trend with the increase of development level (Fleisig et al., 1999), it seemed that the higher the development level, the higher the trunk rotation acceleration was. That is, professional pitchers should generate higher trunk rotation torque relative to the moment of inertia of trunk than college and even youth pitchers did. Until now, there was no kinetic analysis about the trunk rotation in baseball pitching. Therefore, it is not possible to verify the results of these two studies. But it is noticeable that it was reported that the trunk kept rotating since the balance position (Stodden et al., 2001). Therefore, the onset of trunk rotation should not occur again after the SFC. Some definition differences regarding trunk rotation must exist, and makes it hard to interpret the results of these two studies.

Temporal differences in EMG signals were also found between different skill levels. In professional pitchers, the rotator cuff and the biceps were reported more active in the arm cocking but less active in the ACC-phase. Some other muscles, such as the pectoralis major, serratus anterior, subscapularis, and latissimus dorsi, were active mainly in the ACC-phase. But in amateur pitchers, the rotator cuff and the biceps were active through out the ACC-phase (Gowan, Jobe, Tibone, Perry, & Moynes, 1987). Moreover, in a case study, while an experienced Major League pitcher showed high muscle activities in his non-throwing side abdominal oblique and limited the activities in the throwing side during trunk rotation, an inexperienced pitcher fired his both side earlier and at an extremely high level of action (Watkins et al., 1989).

Comparison of Overhand Throwing between Females and Males

Researches comparing the overhand throwing ability between female and male athletes are very limited. Atwater (1970) conducted her doctoral dissertation comparing the kinematic differences of forceful softball throwing between five female collegiate athletes skillful in overhand throwing and five male baseball position players (not pitchers). Several differences were found between genders.

The stride length tended to be shorter in females, both absolutely and relatively to body height. The time from the SFC to the REL was longer in females, the pelvis rotation started earlier in females before the SFC, and the time from the SFC to peak upper torso angular velocity was longer in females. In these variables, the females showed much higher variance, causing the data from males overlapped with the female data, and making the difference probably not significant. The larger variance in females might be due to the fact that those female participants were selected from different sports, having different throwing skills specific to certain sports, while the male participants were all baseball players.

The females were found rotated their trunk more than the males. Until the REL, the females had average 116.4º of pelvis rotation and 130.9º of upper torso rotation, while males had 93.6º and 118.2º, respectively. However, these numbers were overall rotation, not the rotation since the

SFC. As the female started their pelvis rotation earlier, it is not known whether the females rotated their trunk more during the arm cocking and acceleration.

The average peak pelvis rotation angular velocities in females and males were similar, at 682.4 and 619.0º•s^{-1}, respectively. The numbers in upper torso were different; the females were at 952.6º•s^{-1}, much slower than males' 1252.0º•s^{-1}. Although using softball, the numbers in males were comparable to previous male baseball pitching studies. With similar pelvis rotation velocity, it seemed that less angular momentum was appropriately transferred upward to the upper torso. Consider that such peak values occurred earlier in females, the difference could be due to timing issues, as slower pitchers were reported to have earlier peak upper torso angular velocity, and their upper torso would start to rotate earlier, together with the pelvis (Takahashi et al., 2002a).

With less angular velocity and angular momentum at the upper torso, less dragging effect at the throwing arm is expected. Although shoulder external rotation angle was not reported in Atwater (1970), other variables could support this indirectly. During the ST-phase, the ball moves forward with the whole body. At the instant just after the SFC, the lower body is stopped but the upper body moves forward faster than it was, due to the transfer of the linear momentum. The ball, with the upper body, increases its forward velocity in a short period. The linear momentum is soon transferred to angular; the dragging effect of the throwing arm occurs, and the shoulder starts to rotate externally, leaving the hand behind but moving the elbow forward.

The forward velocity of the ball is therefore dropped largely because the ball is left behind with the hand.

In Atwater (1970), a great initial forward acceleration was found among the male participants just after the SFC, and the velocity of the ball in hand then dropped rapidly, marking the occurrence of dragging effect. In contrast, female participants had much less initial peak of ball velocity after the SFC. Although not explained by the original author, this slower velocity was probably due to less linear momentum created in the ST-phase, and the earlier pelvis rotation had transferred some linear momentum to angular. Therefore, the linear momentum transferred to upper torso, and the hand, was less. Moreover, the female participants then also showed less decrease in ball velocity and the deceleration was much less rapid, indicating continuing ball forward movement and smaller dragging effect.

With these additive differences along the kinetic chain between genders, the elbow extension angular velocity was found approximately $3{,}000^{\circ}\cdot s^{-1}$ in males, higher than it of $2{,}000^{\circ}\cdot s^{-1}$ in females. And the average ball velocity in males was $35.45 m\cdot s^{-1}$, while it in females was $23.34 m\cdot s^{-1}$ (Atwater, 1970).

There was only one research focused on female baseball pitching, in which the researchers compared only three kinematic variables from the throwing hand reached the maximum height to the ball release, between Japanese female and male collegiate baseball pitchers. The three kinematic variables were the average angular velocity of upper torso, the angle the upper torso rotated, and the upper torso orientation at the REL (Ito et al., 2005).

That different critical event defined in that study increases the difficulty to compare the results to other previous studies. The maximum height of the throwing hand usually occurs after the SFC. Since the trunk continues rotating after the balance position, the angle the upper torso rotated reported in that study should be less than it reported in previous studies. Similarly, since the trunk does not rapidly rotate until mid-arm cocking, it is expected that the average upper torso angular velocity reported in that study would be higher than it in previous studies.

In Ito et al. (2005), the male pitchers rotated their upper torso in average for 101.9±22.8º, at the velocity of $771.7\pm105.1^\circ\bullet s^{-1}$. The average angle traveled was lower as expected comparing to the number of 130º in Stodden et al. (2001), but similar to the number of 108º in Ishida & Hirano (2004). However, the upper torso angular velocities in arm cocking and acceleration phases were reported by Stodden et al. as 920±120º and 810±230º, respectively. The average angular velocity through out these two phases should be a number between these two values, still higher than the number reported by Ito et al., not in agreement with the expectation. Since the average upper torso angular velocity was found significantly associated with ball velocity, the failed expectation could be explained by the fact that pitchers in Stodden et al. had much faster ball velocity at $35.2\pm1.6m\bullet s^{-1}$, than the number of $30.6\pm2.9m\bullet s^{-1}$ of the pitchers in Ito et al.

Ito et al. (2005) also reported the average angle traveled of the upper torso in female pitchers was 89.5±12.5º, and the average angular velocity was 555.1±79.6º•s^{-1}, both significantly lower than them in male pitchers. The upper torso orientation of female pitchers was 115.2±8.0º, comparable to previous studies using American (Stodden et al., 2001) and Japanese (Ishida & Hirano, 2004) male participants.

The peak upper torso angular velocity should be a better predictor to the ball velocity; however, if you have higher average velocity, you are more likely to have higher peak velocity. Like Stodden et al. (2001), Ito et al. (2005) also found the average upper torso angular velocity was significantly associated to ball velocity. They found the r^2 was 0.42 in males, but interestingly, the r^2 in females was at a much lower value of 0.18. Ito et al. jumped to a conclusion that female pitchers had an impropriate upper torso rotation pattern, and failed to utilize the kinetic chain. Without any other kinematic or kinetic variables along the kinetic chain reported, such conclusion is clearly not convincing. But if compared to other supporting results from Atwater (1970), the conclusion could be plausible.

Anatomical and Performance Differences between Genders

A review work by Wells (1991) organized a thorough comparison of anatomical differences between females and males. Generally, generally have smaller body size than males. Body measurements of an adult female are around 92% in average of the measurements of an adult male. Females have smaller angle formed between the femur neck and shaft, and higher knee valgus angle.

Also, adult females have smaller muscle mass and about 8 to 10% more body fat than males; consequently, females are around two thirds strong as males of comparable age. This ratio is more valid in lower body strength, but gets lower in upper body strength. These differences are almost entirely explained by muscle size, as the strength performance is generally the same if normalized to fat-free body mass or cross-section area of target muscles. However, it was found males are stronger in high speed muscle contraction for unknown reasons, even after normalization. According to another review by Riegger-Krugh and LeVeau (2002), females may require more time to generate maximum force than males. It seems females have lower power output. Most differences above are believed to put disadvantage to females in athletic performance, including throwing.

For simple motor tasks mainly depending on trunk or lower body, females can perform over 80% of males, but for those motor tasks that heavily rely on upper body strength, the ratio could down to 50% or even lower, based on researches involving cadets and firefighters. Overhand throwing, including baseball pitching, involves coordinated activities of both lower and upper body. It is, therefore, expected that females can perform nearly 80% of males in ball velocity.

Throwing distance is positively correlated to throwing velocity. The current world records of javelin throw in women is 73% of it in men.

Estimations of Anthropometric Properties

For the kinetic analyses, the anthropometric properties of each body segment must be estimated. Most previous researchers obtained these properties from cadaver studies (Fleisig et al., 1995). However, those died segments may not represent the true properties of living tissues, and the cadavers used were usually from old or unhealthy people, and may not represent the body composition of young athletes. Moreover, when it comes to gender comparisons, a problem occurs, as those cadaver used for estimating anthropometric properties were generally males.

The anthropometric estimations by Zatsiorsky and Seluyanov (2002) could be an acceptable solution for these problems. They measured body compositions from living bodies using a gamma-scanner method, and use the measurements to develop a set of regression equations. The participants they recruited were young and healthy, and included both males and females.

Not surprisingly, however, the female anthropometric parameters from Zatsiorsky have some limitations. First, while their male data were derived from 100 physically fit participants, only 15 females were used. Moreover, while the male participants used were healthy young adults, typical of the general population of this age group, the female participants were all national athletes who were young adults of greater body height and less body weight than general female population of similar age. However, although not perfect, the Zatsiorsky's equations are still one of the best choices for the current study.

CHAPTER 3

METHODS

Research methods used in the current study are presented in this chapter. The first section includes the selection of participants, and the collection of data. For the second part, data reduction, including the processes used for generating three-dimensional coordinates will first be described. Then, the descriptions and corresponding computational methodology of the kinematic and kinetic variables and the computational methodology will be presented.

Participants

The female participants were selected from the videotaped data obtained at the Women's Division of the 17th Roy Hobbs World Series, held in Fort Myers, Florida, November 6th to 9th, 2005. This championship, held annually, is one of the most competitive in the United States. There were six female baseball teams from different regions of the United States registered to play, and several players in the rosters were selected to play on Team USA for the Women's World Cup in 2004 and 2006. The first day games were at the baseball field of the Lee County Sports Complex, while the second day games were at the Red Sox Training Complex. A total of 11 pitchers who pitched in five of the six games during the first two days and were videotaped by the researcher were selected as the participants for the current study. This study was approved by the Institutional Review Board of The University of Georgia, and the permission of videotaping was given from the Chair of Roy Hobbs Baseball (Appendix A).

The male participants, in contrast, were selected from a pool of pitchers who competed in the XXVI Centennial Olympic Games, held in Atlanta, Georgia, during July 20th to August 2nd, 1996, at the Fulton County Stadium. From a pool of 48 male pitchers who had been videotaped over a six-day period, 11 pitchers were selected as the participants for the current study using criteria described below. The use of 3-D coordinates data of these pitchers was permitted courtesy of the American Sports Medicine Institute (ASMI) (Appendix B). A portion of the kinematics for the full sample of 48 pitchers has been published (Escamilla et al., 2001). I believe that the players of both gender groups represent samples from the population of the best amateur baseball pitchers.

To select the male participants from the original pool of 48 pitchers, first, the researcher discarded the pitchers if their body height and weight information was not available. Second, from the remaining 25 pitchers, it was necessary to select pitchers that use a pitching style typical of American pitchers, as all of the female pitchers were from the United States. Therefore, I removed those from Cuba, Japan, and Korea, as pitching techniques in these countries is distinct from those demonstrated in the United States (Escamilla et al., 2002; Escamilla et al., 2001). From the final pool of 16 pitchers, the final 11 pitchers were selected by age to ensure their ages are comparable to the female group (Dun et al., 2007). Nine of the pitchers were not from the United States; rather, they were from Australia, Italy, and The Netherlands. The coaching of baseball in these countries considerably depends on the support of the United States, so the pitching techniques in these countries should be similar to in the United States. Moreover, in the Olympic study of the 48 male pitchers (Escamilla et al., 2001), kinematics of Americans and pitchers from these countries were not different. Thus, the pitchers' home country should not be a confounding factor influencing the pitching mechanics of the male group.

The participants' information and ball velocity of each group is presented in Table 3.1. To compare the means between the two groups to determine if there were gender differences for these characteristics, independent-samples t-tests were used to compare the means between the two groups ($p < 0.05$).

Table 3.1. Participant Characteristics and Ball Velocity of Females and Males

	Female n = 11	Male n = 11	p value
No. of Right (R) and Left-handed (L) participants	R = 10 L = 1	R = 9 L = 2	
Body Height (cm)	169.5±8.4	187.5±9.1	<0.001*
Body Mass (kg)	74.2±17.2	84.1±7.6	0.104
Age (yrs)	28.9±10.4	25.6±5.4	0.367
Ball Velocity ($m \cdot s^{-1}$)	26.8±1.5	36.3±1.8	<0.001*

* Significant difference, $p<0.05$

Data Collection

To collect female pitching data, a letter of permission to carry out this study was acquired from the commissioner of the Roy Hobb's Baseball, the organization that held the event. Through information provided to the public by the Commissioner Office, basic information of the players was obtained. Since the championship was a public domain event, there was no need to get personal permission from the pitchers to videotape their performances.

As shown in Figure 3.1, to record the female pitching motions during the games, two high-speed video cameras (Pulnix TM-640™, JAI Pulnix Inc., San Jose, CA; 120 Hz, shutter speed = 1/500 s) were set outside the field between the home plate and first base, and between the home plate and the third base. The two cameras were focused on the pitcher's mound and located at an angle of approximately 60º between the cameras. Similar two-camera settings have been widely used in previous field studies (Escamilla et al., 2001; Feltner, 1989; Murray, Cook, Werner, Schlegel, & Hawkins, 2001; Pappas et al., 1985; Werner, Murray, Hawkins, & Gill, 2002). A radar gun (Stalker Sports, Applied Concepts Inc., Plano, TX) located behind home plate was used to record the pitched ball velocity.

A 25-point Peak Calibration Frame^{TM} (Peak Performance Technologies Inc., Englewood, CO) was set on the pitcher's mound before or after the day's recording session (Figure 3.2). The calibration object defined a capture space of approximately 2.2m x 1.6m x 1.9m, sufficient to cover the locations of the pitcher’s body during pitching. The global coordinate system was set by orienting the calibration object. ^{+}X acts in a line oriented from the front edge of the pitching rubber toward the home plate; ^{+}Y parallel to the front edge of the pitching rubber, from third base toward first base; and ^{+}Z was directed upward vertically.

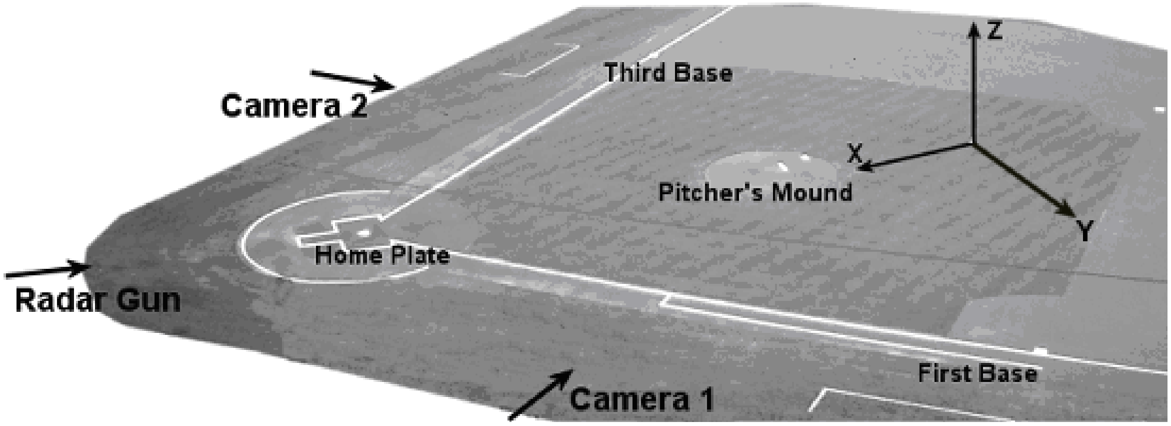


Figure 3.1. Experimental setup and global coordinate system (X.Y.Z.) ^{+}X is oriented from the pitcher’s mound to home plate.

The experimental setup used for collecting for the male pitchers’ data in 1996 was very similar to just described. The same model of high-speed cameras and calibration frame were used, but the locations of the cameras were slightly different (One camera behind the home plate, the other located at the third base), and the shutter speed was set at 1/1000 s. These differences were due to the different designs of the baseball stadium and weather conditions during videotaping. However, it is believed that these differences will not affect the validity of the locations of the reconstructed 3-D coordinates. A different model of radar gun (Jugs Tribar Sport, Jugs Pitching Machine Company, Tualatin, OR) was used capture the male pitcher’s ball velocities. To determine if the velocities reported by both radar guns were similar, the velocities of baseballs projected from a pitching machine in the ASMI laboratory were measured using both guns simultaneously. Their values reported were either the same or varied within 1 mph in the females’ ball velocity range.

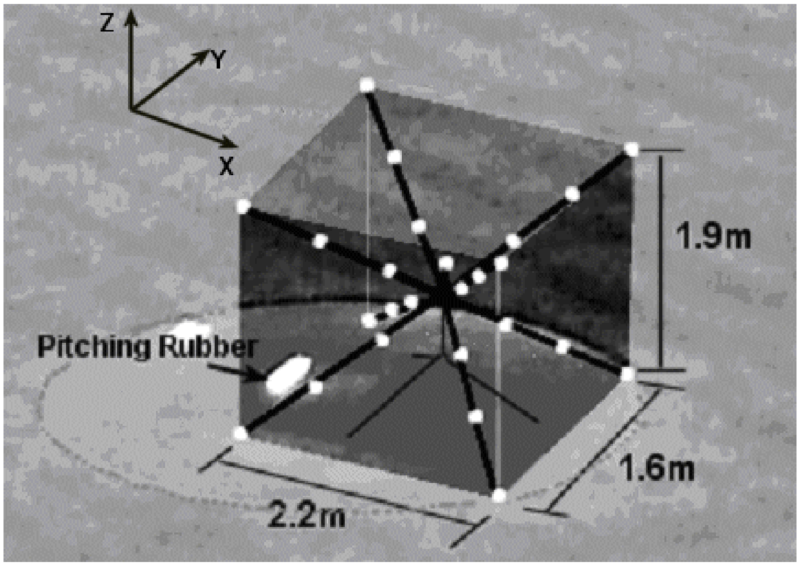


Figure 3.2. Position and orientation of the calibration object and global coordinate system. The video capture volume relative to the pitching rubber also is shown.

Data Reduction

For each of the female pitchers, from the 10 fastball pitches recorded, the pitch demonstrating the highest velocity was the representative trial selected for analysis. A given pitch was classified as a fastball based on the radar gun reading, and with observing the pitcher's motions of the throwing arm and wrist from the videotapes (Escamilla et al., 2001). A fastball can be distinguished from a breaking ball as the index and middle finger are behind the ball instead of below the ball at the instant of ball release, and can be distinguished from a changeup as the ball is gripped differently.

Only one pitch was selected as it has been considered to be representative of a given pitcher's fastball mechanics (Feltner & Dapena, 1986; Fleisig, 1994) and saves hours of time manually digitizing each point of the body for every field of video (Murray et al., 2001). Pappas et al. (1985) analyzed ten pitches for each pitcher, and found the kinematics of each pitcher were "remarkably consistent" across pitches. Furthermore, one-pitch analyses have been widely used in previous studies (Elliott et al., 1986; Feltner, 1989; Feltner & Dapena, 1986; Ishida & Hirano, 2004; Matsuo et al., 2000; Sakurai et al., 1993; Werner et al., 1993; Werner et al., 2002).

The video clips of the selected trials were manually digitized using the methods described in similar studies (Escamilla et al., 2001; Feltner, 1989; Murray et al., 2001; Pappas et al., 1985; Werner et al., 2002) using Peak Motus^{TM} software (v. 9.0, Vicon, Lake Forest, CA). The following 14 points were digitized for both sides of the body: shoulders, elbows, wrists, hips, knees, ankles, and third metatarsals (Figure 3.3). The 3-D spatial locations of each digitized point were reconstructed using a modified DLT method (Miller, Shapiro, & Mclaurin, 1980; Shapiro, 1978). The instants of stride foot contact and ball release were defined as the initiation and termination of the pitching motion.

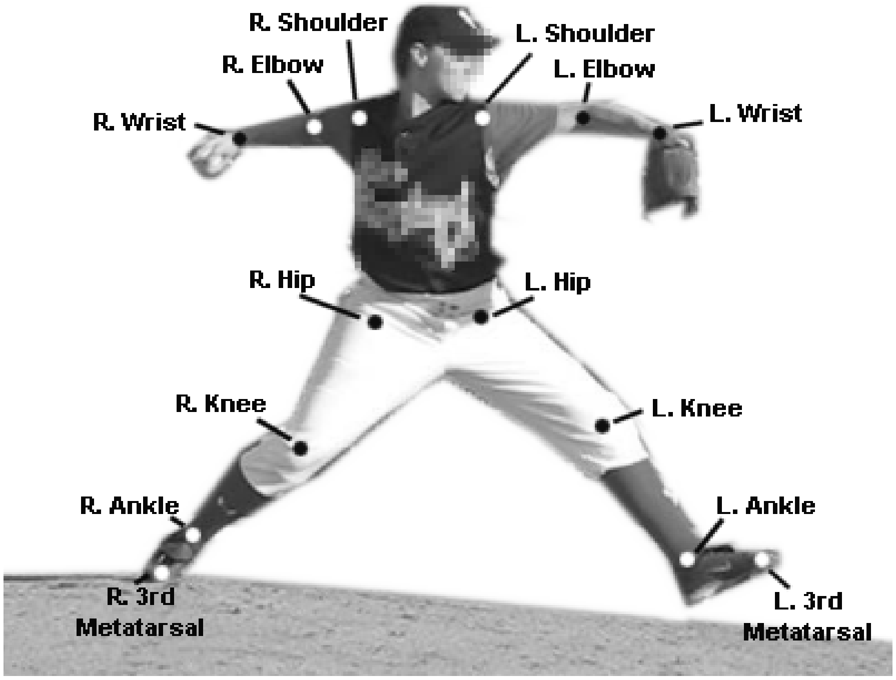


Figure 3.3. Fourteen points of the body digitized and used to define the anatomical model

For a given male pitcher, selected for analysis was the fastest pitch exhibited from the first 10 pitches of the game and that had been previously digitized using a previous version of the same digitizing software (Peak5^{TM}, Peak Performance Technologies Inc., Englewood, CO). As the original videotapes of the male pitchers were not available anymore, the current researcher could not re-digitize them. Therefore, the 3-D reconstructed data digitized by previous researchers were used. Consequently, the inter-digitizer reliability could have been affected. To minimize this problem, the current researcher learned the digitizing methods used in the previous study directly from one of the previous researchers (G. S. F.) before digitizing the female data.

The reconstructed 3-D coordinates were filtered using a low-pass Butterworth filter at the cut-off frequency of 13.4 Hz (Escamilla et al., 2001). The software used was EVa Real-Time software (v. 5.0, Motion Analysis Corp., Santa Rosa, CA) for the female data and the Peak5^{TM} software for the male data.

Data Analysis

To generate all kinematic and kinetic variables, the methodology of Fleisig (1994) was followed, using custom Matlab^{TM} (v. 7, MathWorks Inc., Natick, MA) programs. The details of these programs are presented in Appendix C. To determine the initiation and termination of the pitching motion, Flesig's (1994) criteria were used. The SFC was defined as the last video field that the stride ankle or the 3rd metatarsal moved at least $1.5 \mathrm{m} \bullet \mathrm{s}^{-1}$. The REL was defined as the next field after the wrist passed the elbow in global $^{+}\mathbf{X}$ direction.

Kinematic Analysis

The segmental coordinate systems used are shown in Figure 3.4. Vectors were used to define the orientations of several segments. The upper torso was defined as the vector from the non-throwing shoulder to the throwing shoulder; the pelvis was defined as the vector from the stride hip to the throwing hip. The vector from the mid-point of shoulders to the mid-point of hips defined the trunk.

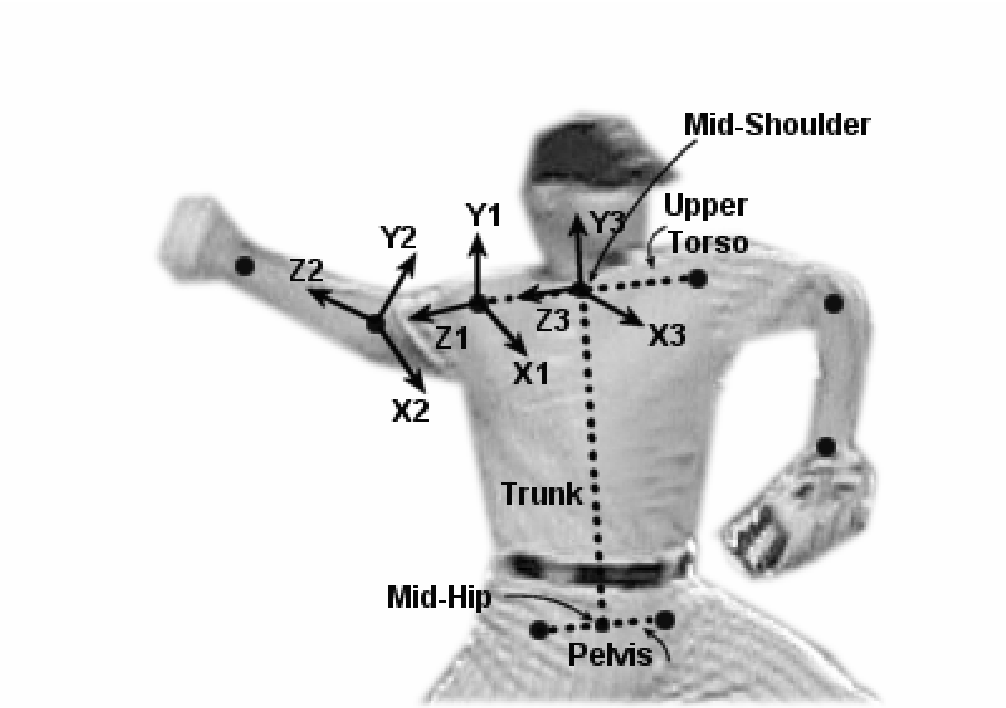


Figure 3.4. Local coordinate systems, upper torso, pelvis, and trunk

To calculate the kinematic variables of the throwing shoulder, using Fleisig's conventions (1994), a local coordinate system was defined based on the alignment of the pitcher's trunk. The direction vector $\mathbf{Z_3}$ was defined from the mid-point of the shoulders toward the throwing shoulder; $\mathbf{X_3}$ pointed anteriorly from the mid-shoulder and was defined as the cross product of a vector from mid-hip to mid-shoulder and $\mathbf{Z_3}$; $\mathbf{Y_3}$ pointed upward from mid-shoulder, and was defined as the cross product of $\mathbf{Z_3}$ and $\mathbf{X_3}$ (Figure 3.4). The vectors $\mathbf{Z_3}$ and $\mathbf{X_3}$ defined the transverse plane, the vectors $\mathbf{Z_3}$ and $\mathbf{Y_3}$ defined the frontal plane, and the vectors $\mathbf{Y_3}$ and $\mathbf{X_3}$ defined the sagittal plane.

Figures 3.5 to 3.7 show the definitions of the angles used in this study. The upper torso orientation angle is the angle between the upper torso vector and the $^{+}\mathbf{X}$ GCS vector (Figure 3.5). When this angle is zero, the upper torso is parallel to $^{+}\mathbf{X}$. Similarly, the pelvis orientation is the angle between the pelvis vector and the $^{+}\mathbf{X}$ GCS vector. The upper torso/pelvis separation angle is defined as the angle between the upper torso and the pelvis.

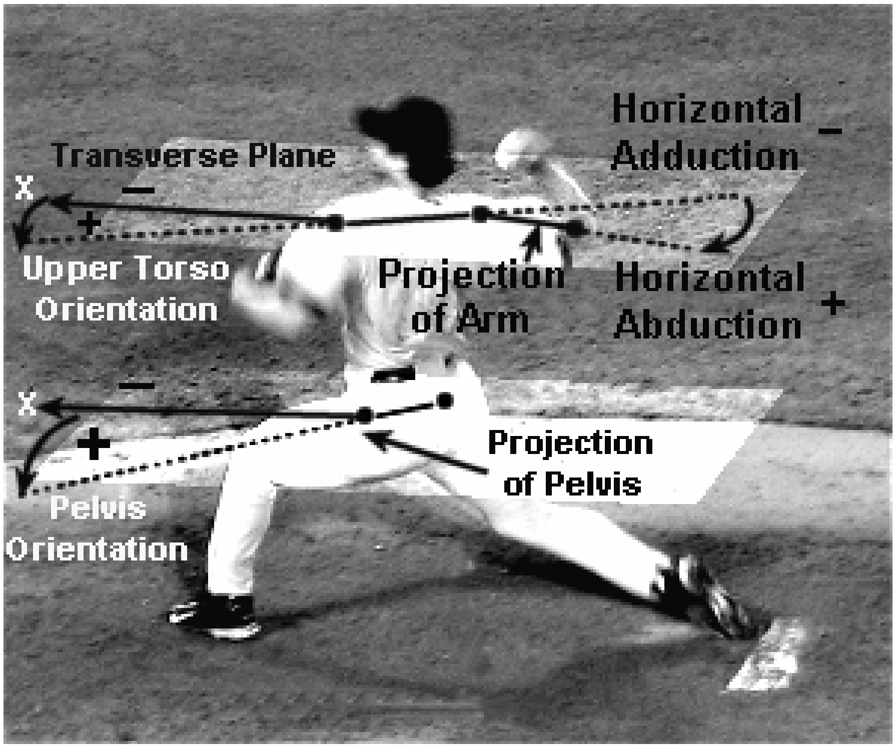


Figure 3.5. Shoulder horizontal ab/adduction, upper torso and pelvis orientation

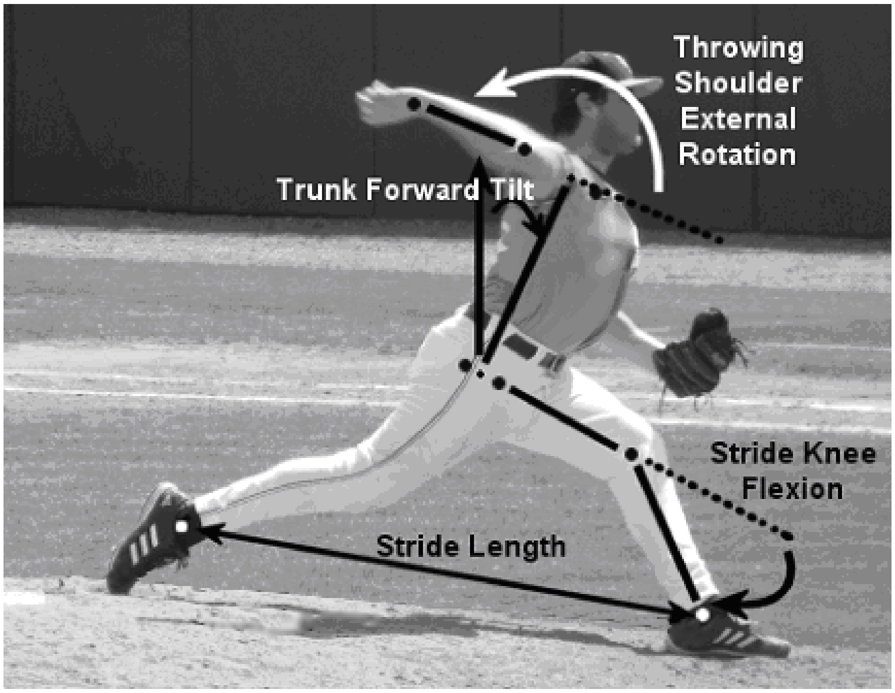


Figure 3.6. Shoulder external rotation, stride length, and trunk forward tilt

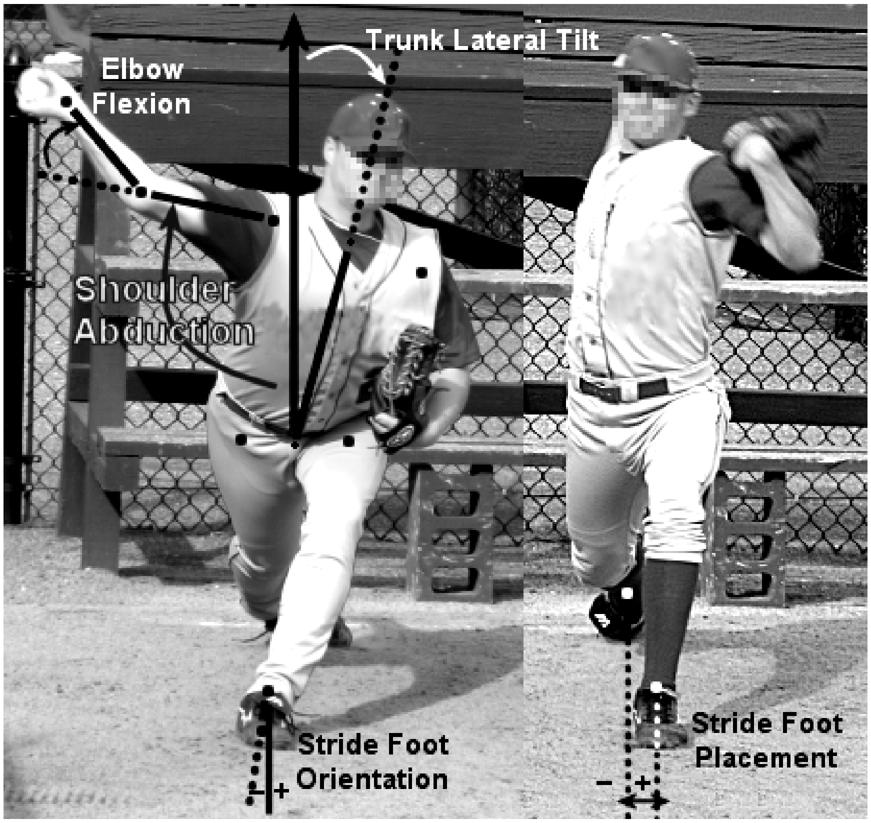


Figure 3.7. Trunk lateral tilt, stride foot and placement, and elbow flexion

The throwing shoulder angles are shown in Figure 3.5 to 3.7 horizontal ab/adduction, int/external rotation and ab/adduction, respectively. The horizontal ab/adduction angle is the angle formed by $\mathbf{Z_3}$ and the projection on the transverse plane of the upper arm. The ab/adduction is the angle formed by $\mathbf{-Y_3}$ and the projection on the frontal plane of the upper arm. The int/external rotation angle is the angle formed by forearm and $\mathbf{X_3}$ both projected on a plane perpendicular to the upper arm.

Other angles of interest are shown in Figures 3.6 and 3.7. The throwing elbow flexion angle is the angle between distal directions of the upper arm and the forearm. Similarly, the knee flexion angle is the angle between the distal directions of the thigh and the shank. The trunk forward tilt is the angle between the trunk and the $^{+}\mathbf{Z}$ direction on XZ plane, and the trunk lateral tilt is the angle between the trunk and the $^{+}\mathbf{Z}$ direction on YZ plane. The stride length at the SFC is the distance between the ankles. The stride foot placement is the distance between the ankles in $^{+}\mathbf{Y}$ direction. The stride angle is the angle between the stride foot and the $\mathbf{+X}$ direction.

Kinematic variables are shown in Table 3.2. Variables obtained for angle and angular velocity data include the magnitudes displayed at selected critical events and maximum values were calculated, as well as the angular velocities.

Table 3.2. Kinematic variables

Balance position (BAL)
Stride knee maximum height (%BH, cm above stride hip)
Upper torso and pelvis orientation (°)
Stride foot contact (SFC)
Stride knee flexion angle (°)
Stride foot placement (m)
Stride length (%BH)
Stride orientation (°)
Upper torso and pelvis orientation (°)
Upper torso/Pelvis Separation (°)
Throwing shoulder abduction, horizontal abduction, and external rotation angle (°)
Throwing elbow flexion angle (°)
Maximum shoulder external rotation (MER)
Throwing shoulder abduction, horizontal abduction, and external rotation angle (°)
Throwing elbow flexion angle (°)
Ball release (REL)
Stride knee flexion angle (°) and extension angular velocity (°•s^{-1})
Upper torso and pelvis rotation (°)
Trunk forward and lateral tilt angle (°)
Throwing shoulder abduction, horizontal abduction, and external rotation angle (°)
Throwing elbow flexion angle (°)
Other Peak Angular Velocities during Arm Cocking and Arm Acceleration Phases
Upper torso and pelvis maximum angular velocity (°•s^{-1})
Throwing shoulder max internal and horizontal adduction rotation angular velocity (°•s^{-1})
Throwing elbow maximum extension angular velocity (°•s^{-1})

Temporal variables are shown in Table 3.3. These variables include the times when the maximum angles and angular velocities occur, and are scaled relative to the total time of the pitching motion (REL T).

Table 3.3 Temporal Values regarding Kinematic Variables

Relative time (% REL T) of
Max pelvis angular velocity
Max upper torso angular velocity
Max trunk forward tilt angular velocity
Max stride knee extension angular velocity
Max shoulder external rotation
Max shoulder internal rotation angular velocity
Max elbow flexion
Max elbow extension angular velocity
Absolute time (sec) between SFC and REL

Kinetic Analysis

Equations of Zatsiorksy and Seluyanov (Zatsiorsky, 2002) were used to generate anthropometric values. Their models were chosen because their data are specific to both genders and based upon participants of ages similar to those in the present study.

Inverse Newtonian dynamics methodology was applied to compute the components of net joint forces and torques for the throwing shoulder and elbow, as shown in Figure 3.4. Two local coordinate systems were defined at the throwing shoulder and elbow, respectively, to resolve the forces into components. For the shoulder, vector $\mathbf{Z}_1$ is the longitudinal axis of arm, $\mathbf{X}_1$ is the anterior direction of shoulder, and $\mathbf{Y}_1$ is the superior direction of shoulder. $\mathbf{X}_1$ is calculated as the cross product of trunk and $\mathbf{Z}_1$, while $\mathbf{Y}_1$ is the cross product of $\mathbf{Z}_1$ and $\mathbf{X}_1$. Similarly, the distal, medial, and anterior vectors at the elbow were defined as $\mathbf{Z}_2$, $\mathbf{X}_2$, and $\mathbf{Y}_2$. $\mathbf{Z}_2$ is the longitudinal axis of forearm, $\mathbf{X_2}$ is the cross product of $\mathbf{Z_2}$ and $\mathbf{Z_1}$, while $\mathbf{Y_2}$ is the cross product of $\mathbf{Z_2}$ and $\mathbf{X_2}$. In addition to reporting absolute magnitude, the forces are also scaled to body height (%BH), and the torques are scaled by body weight and height (%BW*BH).

Due to its small mass and difficulty accurately locating its spatial location, the throwing hand was modeled at the position of the wrist (Fleisig, 1994). The mass of ball was set at 0.145 kg and also located at the wrist position before the REL, due to limited resolution of video. The kinetic variables to be analyzed are presented in Table 3.4.

Table 3.4. Kinetic Variables

Maximum elbow proximal force (N, %BW)
Maximum shoulder proximal force (N, %BW)
Maximum elbow varus torque (Nm, %BW*BH)
Maximum shoulder internal rotation torque (Nm, %BW*BH)

Statistical Analysis

Gender differences were tested for each variable using SPSS (v. 11.5, SPSS Inc., Chicago, IL), and evaluated at $p<0.05$. For all variables, to compare means of the gender groups, independent-sample t-tests were used. To ensure the assumptions of t-test not violated, Levene's Test and one-sample Kolmogorov-Smirnov tests were run for homogeneity of variance and normality, respectively. If either homogeneity or normality assumption was violated, two-sample Kolmogorov-Smirnov Tests (K-S test) were used instead. Effect sizes (ES) were calculated using

Cohen’s d with pooled standard deviation to verify the behavioral meaning of statistical significance. An ES larger than 0.8 was large (Cohen, 1988) and considered having behavioral meanings..

CHAPTER 4

RESULTS

Data Accuracy and Reliability

Prior to presenting the outcomes of the study, reporting the accuracy of the 3-D reconstruction is valuable. To test the accuracy of the DLT equations for 3-D reconstructions, the reconstructed coordination of 25 points of the calibration frame was compared to known coordinates reported by the manufacturer of the frame. For male data, an average root mean square error of calibration was 0.008 m (Escamilla et al., 2001). Similarly, for females, for the first and second day of data collection, this calibration error was 0.011 and 0.008 m, respectively.

Intra-researcher reliability for digitizing the male data was reported by the previous researchers (Escamilla et al., 2001). One researcher digitized the three trials, displaying differences of 0.01 to 0.02 m for calculated segment lengths. A similar approach was applied to the female data. One month after the first digitizing session, I re-digitized seven video fields of the fast-moving COC and ACC phases for two trials. Compared to the data of the original digitizing session, for the lengths of the humerus and radius, the re-digitized trials yielded a comparable range of difference: 0.005 to 0.014 m. These differences decreased to less than 0.002 m after filtering. This indicats that some amount of intra-researcher digitizing errors can be removed when using the selected cut-off frequency, and thus, this type of error should have minimally affected the result of the 3-D reconstruction.

Inter-digitizer reliability could not be established, as the current researcher was unable to digitize the male data. However, for the male data, Escamilla et al. (2001) reported inter-digitizer difference for selected segment lengths of 0.01 to 0.02 m among three different researchers. This indicates the existence of good digitizing standards to follow and the task of identifying joint centers of baseball pitching video is objective enough that different digitizers could generally find the same target. Therefore, to minimize technique error, I digitized the female data based on the techniques that I learned and practiced from one of the previous researchers (G. S. F.). Thus, it is assumed that I digitized my female data as comparably to the male data as possible under the circumstances, although I acknowledge that there is still some small potential for systematic spatial error.

Kinematics

For the female pitchers, the means of the variables exhibited at the instant of balance position (BAL) and stride foot contact (SFC) are presented in Tables 4.1 and 4.2, respectively. Unfortunately, the acquired dataset of males did not contain the 3-D coordinates at the instant of BAL; therefore, comparison between gender groups was not possible.

As shown in Table 4.2, three of eleven SFC variables displayed significant p-values for gender comparisons. All of these three variables have effect sizes larger than 0.8, indicating that the differences detected are behavioral meaningful. No variables were significantly different at the instant of MER (Table 4.3).

Table 4.1. Mean±SD for Body Positioning Displayed at Balance Position by Females

Variable	Means±SD
Stride Knee Max Height (%BH)	50.2±8.6
Stride Knee Max Height (cm above stride hip)	3.2±13.9
Upper Torso Orientation (º)	-24±13
Pelvis Orientation (º)	-18±9

For kinematics at ball release (Table 4.4), stride knee flexion and pelvis rotation at the REL were significantly different between genders. That is, females had a more flexed knee joint and more rotated pelvis. Knee extension angular velocity was much lower for females, while trunk lateral tilt (p=0.061) for females tended to be lower but marginally failed to reach statistical significance. Females also exhibited higher maximum pelvis angular velocity, but lower maximum elbow extension angular velocity (Table 4.5). All of these significant variables have large effect sizes.

Table 4.2. Mean±SD for Kinematic Variables Exhibited at Stride Foot Contact and Gender Comparison Outcomes

Variable	Female	Male	p-value	Effect Size
Lower Body				
Stride Knee Flexion (º)	50±14	55±16	0.464	0.32
Stride Foot Placement (m)	-0.01±0.14	-0.14±0.10	0.018*	1.10
Stride Length (%BH)	70.3±8.4	78.4±6.7	0.021*	1.07
Stride Orientation (º)	-5±19	-5±13	0.965	0.02
Trunk				
Upper Torso Orientation (º)	-5±21	-17±14	0.144	0.65
Pelvis Orientation (º)	34±15	39±13	0.673	0.33
Upper Torso/Pelvis Separation (º)	40±15	56±15	0.018*	1.10
Throwing Arm				
Throwing Shoulder Abduction (º)	99±13	91±7	0.076 [a]	0.78
Throwing Shoulder Horiz. Abduction (º)	19±18	22±15	0.666	0.19
Throwing Shoulder External Rotation (º)	59±35	54±24	0.679	0.18
Throwing Elbow Flexion (º)	98±25	97±26	0.897	0.06

Note. *Female and male groups significantly different ($p < 0.05$)

[a] Assumption of homogeneity of variance violated, using p-value from K-S test instead

Table 4.3. Mean±SD for Kinematic Variables Exhibited at the Maximum Shoulder External Rotation and Gender Comparison Outcomes

Variables	Female	Male	p-value	Effect Size
Throwing Arm				
Throwing Shoulder Abduction (º)	91±6	86±9	0.186	0.58
Throwing Shoulder Horiz. Adduction (º)	2±12	5±14	0.563	0.25
Throwing Shoulder External Rotation (º)	179±13	171±8	0.076[a]	0.75
Throwing Elbow Flexion (º)	87±15	81±18	0.410	0.36

[a] Assumption of homogeneity of variance violated, using p-value from K-S test instead

Table 4.4. Mean±SD for Kinematic Variables Exhibited at the Ball Release and Gender Comparison Outcomes

Variables	Female	Male	p-value	Effect Size
Lower Body				
Stride Knee Flexion (°)	62±14	41±19	0.008*	1.26
Stride Knee Extension Ang. Vel. ($°\bullet s^{-1}$)	81±187	317±180	0.007*	1.65
Trunk				
Upper Torso Rotation (°)	118±25	121±19	0.648	0.20
Pelvis Rotation (°)	58±15	33±12	<0.001*	1.87
Trunk Forward Tilt (°)	28±7	33±13	0.252	0.50
Trunk Lateral Tilt (°)	16±11	25±10	0.061	0.85
Throwing Arm				
Throwing Shoulder Abduction (°)	89±6	90±10	0.461[a]	0.14
Throwing Shoulder Horiz. Adduction (°)	9±8	7±15	0.688	0.17
Throwing Shoulder External Rotation (°)	136±14	122±29	0.139	0.66
Throwing Elbow Flexion (°)	31±10	27±7	0.247	0.51

Note. *Female and male groups significantly different ($p < 0.05$)

[a] Assumption of homogeneity of variance violated, using p-value from K-S test instead

For the temporal characteristics of the kinematics, none of the relative times that peak angles or angular velocities occurred were found significant, but the p-value of the timing of maximum knee extension angular velocity almost reached the threshold (p=0.051) (Table 4.6). On the other hand, the absolute time between the SFC and the REL of females compared to males was approximately 0.02 s longer, and the difference was statistically significant. The effect sizes of these variables are large.

Table 4.5. Mean±SD for Peak Angular Velocities during Arm Cocking and Arm Acceleration Phases and Gender Comparison Outcomes

Variables	Female	Male	p-value	Effect Size
Trunk				
Upper Torso Max Angular Vel. ($^{o}\bullet s^{-1}$)	1187±236	1247±201	0.519	0.28
Pelvis Max Angular Vel. ($^{o}\bullet s^{-1}$)	700±243	423±195	0.008*	1.25
Throwing Arm				
Shoulder Max Internal Rotation Ang. Vel. ($^{o}\bullet s^{-1}$)	5630±1585	5845±2399	0.807	0.11
Shoulder Max Horiz. Adduction Ang. Vel. ($^{o}\bullet s^{-1}$)	657±253	751±241	0.384	0.38
Elbow Max Extension Ang. Vel. ($^{o}\bullet s^{-1}$)	2062±365	2980±738	0.001*	1.58

Note. *Female and male groups significantly different ($p < 0.05$)

Table 4.6. Mean±SD for Temporal Variables and Gender Comparison Outcomes

Variables	Female	Male	p-value	Effect Size
Relative Time (REL T) to Maximum:				
Pelvis Ang. Vel. (%REL T)	33±26	33±32	0.997	0.00
Upper Torso Ang. Vel. (%REL T)	56±17	42±19	0.075	0.80
Trunk Forward Ang. Vel. (%REL T)	104±27	89±12	0.111	0.71
Knee Extension Ang. Vel. (%REL T)	120±24	98±26	0.051	0.89
Shoulder External Rotation (%REL T)	76±10	81±5	0.169	0.61
Shoulder Internal Rotation Ang. Vel. (%REL T)	107±4	105±7	0.309	0.45
Elbow Flexion (%REL T)	39±18	30±22	0.274	0.48
Elbow Extension Ang. Vel. (%REL T)	95±5	93±4	0.478	0.31
Absolute from SFC to REL (sec.)	0.163±0.026	0.141±0.021	0.048*	0.92

Note. *Female and male groups significantly different ($p < 0.05$)

Kinetics

Descriptive and statistical outcomes for the four selected kinetic variables are shown in Table 4.7, presented in both absolute and scaled values. All four kinetic variables were significantly different between groups when presented in absolute magnitude. The forces acting on the elbow and shoulder, when scaled to body mass, were greater for the male than the female group. Significant differences were not detected for torques scaled to body mass and heights.

Table 4.7. Mean±SD for Peak Forces and Torques Exhibited during Pitching and Gender Comparison Outcomes

Variables	Female	Male	p-value	Effect Size
Max Elbow Proximal Force (N)	453±60	1054±468	<0.001*	1.80
Scaled (%BW)	64±10	128±54	0.001*	1.63
Max Shoulder Proximal Force (N)	510±108	1231±419	<0.001^{a}*	2.36
Scaled (%BW)	73±25	150±50	<0.001*	1.95
Max Elbow Varus Torque (Nm)	46±9	86±49	0.023^{a}*	1.15
Scaled (%BW*BH)	4±1	5±3	0.076^{a}	0.83
Max Shoulder Internal Rotation Torque (Nm)	48±11	88±46	0.023^{a}*	1.19
Scaled (%BW*BH)	4±1	6±3	0.206^{a}	0.86

Note. *Female and male groups significantly different ($p < 0.05$)

^{a}Assumption of homogeneity of variance violated, using p-value from K-S test instead

Noticeably, the variances of kinetic values in males were much larger than in females, with coefficients of variation (the ratio of the standard deviation to the mean) of the variables ranging from 0.53 to 1.05 for the males, and 0.13 to 0.23 for females. The variability for males for the joint torque variables were even higher than for the force variables, and therefore, may have influenced the ability to detect significant differences between groups for the joint torques.

The sources of the high variability of the male sample are not known, but may represent true inter-participant variability, unknown methodological errors, differences in technique based on the country of origin, etc. However, inter-participant variability for the male pitchers of this study is within reason. First, inter-participant differences for joint forces greater than 200 N or 55% of the mean value have been reported in some studies (Fleisig, Escamilla, Barrentine, Zheng, & Andrews, 1996; Fleisig, Zheng et al., 1996), indicating such degrees of variability exist. Moreover, the kinetic values were calculated based on kinematic variables. While the current male kinematic data that the kinetic calculations based on are also similar to other previous studies, it seems there is no reason to suspect that the current variability invalid.

CHAPTER 5

DISCUSSION

The main purpose of the current study was to identify the biomechanical features of elite females pitching fastballs to understand how baseball pitching is accomplished by females. Second, it was of interest to compare the mechanics of the female pitchers to skilled, amateur male pitchers. The biomechanics of a total of 22 pitchers (11 females, 11 males) were analyzed in the current study.

Before interpreting the gender comparisons, note that potential influences of slight differences in data collection and video digitizing processes may have affected differentially the male and female data. However, it is expected that the bias is limited, as all other procedures and computations were equivalent. The participant samples otherwise appear robust. Levene’s test for equality of variances was applied to all kinematic variables. Among all 30 kinematic variables, only shoulder abduction at the SFC ($p=0.025$) and at the REL ($p=0.022$), and shoulder external rotation at the MER ($p=0.019$) showed unequal variance between genders at the significance level set at 0.05. Moreover, both the mean value and variance for the male group were similar to previous baseball pitching studies. As variances in kinematics were also found similar among different groups with different body size and strength (Fleisig et al., 1999), similar to the main inherited differences between female and male, these facts suggest that the current sampling was enough to cover individual differences of pitchers.

Based on physiological and morphological differences between females and males, I had predicted that females and males would display different kinematics and kinetics. In general, it was anticipated that due to males having the higher physiological capacity to create greater muscle force and power than females, the maximum joint forces and torques would be lower for females than males. The consequences of differing kinetics were predicted to also affect the kinematics. Therefore, the global outcome score (i.e., the culminating feature of the pitching mechanics), that is, ball velocity, also was expected to be lower for the females than the males. As predicted, compared to females, males were significantly taller, and maybe heavier (although not statistically significant, probably due to high variance of females' body weight). Ball velocity was significantly lower for the female pitchers. In addition, there was still a six mph difference between the fastest female and the slowest male pitch velocity. Kinetic and kinematic differences were detected as predicted.

Kinetic Differences and Risks of Injury

The predictions of lower joint torques and forces created by the female compared to male pitchers were supported, as all components of joint torques and forces at the throwing shoulder and elbow joints were lower for females. The results of non-normalized torque values and joint forces being lower for the females than males are not surprising, possibly due to the surmised muscle strength differences, although this cannot be directly proven.

There are two major consequences of these differences: lower ball velocities for female pitchers and, potentially, reduced injury potential. In this section, I will address the consequences of lower joint torques and forces on injury potential.

For males, some of the kinetic values are thought to be of high enough magnitudes to cause injuries (Fleisig, Barrentine et al., 1996). For example, previously-reported value of elbow varus torque, a very important variable correlated to ulnar collateral ligament (UCL) injury, was generally more than 60 Nm in adult male pitchers (Table 2.10). Fleisig, Barrentine et al. (1996) surmised this value to be close to the limit of non-damaging loading on the UCL, as cadaver testing showed 55% of varus torque is resisted by the UCL at 90º elbow flexion (Morrey & An, 1983), and the maximum torque that an UCL cadaver specimen can produce before failing was shown to be 32.1±9.6 Nm (Fleisig et al., 1995). This probably explains the prevalence of UCL reconstruction surgery (a.k.a., Tommy John surgery) in elite male pitchers, albeit testing the strength of a ligament from cadavers in vitro may not represent the tension a living ligament can tolerate in vivo. In the current study, the male pitchers exhibited an average value of 84 Nm of this variable. This value is quite high, although still within the range of previously reported values (Table 2.10). An average torque of approximately 46 Nm, therefore, is estimated to be resisted by the UCL for the current male pitchers. In contrast, there are only around 26 Nm of average torque resisted by the UCL of female pitchers.

Although the much lower absolute torques in females may indicate lower risk of injury, the possibility is, of course, not zero. The estimated torques across the UCL for females are generally, but not always, under the line of failure. One female pitcher in the current study showed a peak elbow varus torque at 62 Nm, that is, 34 Nm of torque is estimated to be resisted by her UCL. Moreover, individual difference of UCL durability should not be overlooked, and it is not known if females have similar ligament morphology and durability that may potentially affect the injury risks.

For the throwing shoulder, the structure is much more complex than the elbow. Although some explanations of shoulder injury mechanisms are provided (Fleisig et al., 1995; Fleisig, Barrentine et al., 1996), it is still not clear how much the force or torque would damage which part of shoulder. However, it is clear that the magnitude of forces and torques applied on the shoulders are considerably great. It should be noticed that a more open foot placement, currently found in females, was found relative to higher shoulder load (Fleisig, 1994). This issue should be addressed when coaching female pitchers in order to reduce the risk of shoulder injuries.

Even if the forces and torques do not directly cause the rupture of tissue, repeated occurrence of such degrees of loads still develop microtrauma, which may accumulate and finally lead to overuse injury (Fleisig et al., 1995), and female athletes are suspected more prone to this type of injury compared to males (Beasley, Faryniarz, & Hannafin, 2000). An emerging consensus regarding this issue is that the amount of pitching of young pitchers should be carefully monitored on both event and season basis (Lyman et al., 2002; Olsen, Fleisig, Dun, Loftice, & Andrews, 2006; Petty, Andrews, Fleisig, & Cain, 2004), and new pitch count rules have been enforced for every pitchers in some youth to high school leagues ("Regulation and Rule Changes for 2007," 2006). The current female pitchers exhibited force and torque magnitudes similar to those reported for youth male baseball pitchers who also had comparable body height to the female pitchers (Fleisig et al., 1999). Accumulated pitch count gamely or seasonally still increase the risk of pain or more severe injuries in youth pitchers despite of lower joint forces and torques (Lyman et al., 2002). Although adult female pitchers should be have higher maturity in skeletal development than youth baseball pitchers, the risk of overuse should never be neglected.

Kinematic Features of Female Baseball Pitching

Physiological and morphological differences between genders produce different kinetic features performing baseball pitching, and present as different kinematic attributes that can be observed. Females were expected to have several kinematic characteristics that different to males, such as shorter stride, more open foot placement and orientation, more open upper torso and pelvis and less separation between these two segments at stride foot contact, and less shoulder external rotation angle, less trunk tilt forwardly and laterally, more flexed knee, and less knee extension angular velocity at ball release.

At the Instant of Balance (BAL)

For the kinematics at the instant of balance, females were expected to have more open upper torso and pelvis orientation angle, and lower height of stride knee, indicating less trunk backward rotation and less leg lift during the windup phase, respectively. The facts of less muscle strength may underlie these characteristics of females. The higher the stride knee lifted, the higher the COM of the body, requiring better strength in support leg and hip to keep the body balanced at the instant of BAL. The fact that coaches usually instruct pitchers to lift their stride leg to the most comfortable and balanced height suggests females may not have enough strength to balance their body with a high leg kick.

Although not provable due to no male data were available for the current study, these expectations may have some merit. For trunk rotation, the magnitudes of female orientation angles for the upper torso (-24±13º) and pelvis (-18±9º) were less than those reported by Stodden et al. (2001) (-30±13º and -36±13º, respectively). Moreover, for the leg lift, the female pitchers exhibited only 3.2±13.9 cm for the knee height above the hip, compared to 33.1±4.1 cm reported by Elliott et al. (1986). These values were not normalized to body height, but it is clearly that females only lift their knee to around the height of hip, while males lift the knee way above the hip.

At the Instant of Stride Foot Contact (SFC)

The less strength in the lower body and the trunk should continue to contribute to the kinematic features of females at the SFC. For example, an expected shorter and probably slower stride in females may be both a direct consequence of lower leg kick creating less potential energy to be utilized, and a sign that less force the support leg could generate to drive the body forward. Moreover, during the stride (ST-phase), the base of support is only the area that the support foot contacts the ground. Therefore, the longer the stride length, the farther the COM of body out of the base of support, the less GRF in vertical direction to counteract the body weight, and the harder to maintain a smooth and stable body forward shift and a consistent foot landing. To reach a long stride, these difficulties can only be offset by a strong drive by the support leg.

Other kinematic features of females at the SFC may be affected by some characteristics displayed in early phases. For example, with probably more open (i.e., facing the home plate) upper torso and pelvis orientation angles at the BAL, females would have these two angles also more open at the SFC. While these two angles indicate that the trunk is more open, it is likely that the stride foot is also oriented (angular) and placed (positional, please refer to Figure 3.7) more open.

These variables are not only the checkpoints of the finished stride phase, but also important to the performance of following phases. For example, a shorter stride are believed relative to less body stretch and therefore lower ball velocity (Dillman et al., 1993), and both open foot placement and orientation are found relative to increased peak force acting on throwing shoulder (Fleisig, 1994). The most important variable is the separation angle between pelvis and upper torso. With such a “twist” between the pelvis and upper torso, the trunk is more likely to rotate sequentially downside up, which is a sign of mature throwing mechanics, instead of a blocked trunk rotation (Stodden, Fleisig, Langendorfer, & Andrews, 2006a). Less magnitude of this angle for females allows less room for abdominal oblique, which will then highly activated during the upcoming arm cocking phase (COC-Phase) (Watkins et al., 1989), to store elastic energy and contribute to the rapid rotation of upper torso (Fleisig, Barrentine et al., 1996).

Based on the results of the current study, the shorter stride, the open foot placement, and the greater upper torso/pelvis separation angle have been verified as features of female pitching; however, not all hypotheses at the SFC were supported. Although with more open foot placement, females aligned their stride foot at the similar orientation as males. Also, either due to an earlier initiation of transversal rotation earlier during the stride (Dillman et al., 1993), or due to a more open pelvis orientation at the BAL before the initiation of stride (like in the current case), an open foot placement can be caused by an open pelvis orientation. However, interestingly, the pelvis orientation of females was not statistically different to it of males.

While no significant difference of the pelvis orientation was detected between genders, the more open stride foot placement found in females may suggest a higher stride hip internal rotation, a higher stride knee valgus angle, or both. Therefore, it is suspected that besides the strength gap, the structural differences, such as the generally greater knee valgus angle in females (Riegger-Krugh & LeVeau, 2002), may also play some roles for the female-specific kinematic features. This difference in knee valgus does not exist only statically (Hunter, 1984), but also found dynamically in many different motor tasks. For example, throughout a task of single leg drop landing off a 60 cm height platform, which in some degrees similar to the landing of stride foot in pitching, the stride knee of females was more valgus than males (Russell, Palmieri, Zinder, & Ingersoll, 2006). With the angle definition in the current study, the knee flexion angle calculated may actually include both knee flexion and the varus/valgus angle. While females have shorter stride length, it is more likely they also have smaller knee flexion angle at the SFC, as the COM of body is higher. Thus, the knee flexion angle in females, although found similar to males, may actually be a composition of knee flexion and valgus.

During the Arm Cocking Phase (COC-phase)

During the arm cocking, the pelvis and the upper torso peak their rotation velocities sequentially, creating the inertial lag effect to make the throwing arm rotate externally. Therefore, a successful performance during this phase is marked by a rapid rotation of upper torso, which is achieved by proper up-transfer of angular momentum from the pelvis, and the quick contraction of abdominal oblique.

In the current study, females' peak pelvis angular velocity was, surprisingly, higher than males'. However, this number is actually very similar to males' value reported in most previous studies (Table 2.4). In contrast, it was the male participants in the current study performed low pelvis angular velocity, although comparable value is still available (Ishida & Hirano, 2004). On the other hand, male participants performed peak upper torso angular velocity comparable to most previous studies, while females had the magnitude of this variable at the very low end of previous studies, although still comparable (Table 2.4).

Although peak upper torso angular velocity in females is not significant lower than males, longer time spent to achieve this value (Table 4.6) still indicates less torque from the lateral abdominal muscles output in the COC-phase. The numbers of these two variables for females also supports that less separation angle between pelvis and upper torso at the SFC leads to less energy transfer. In contrast, while the pelvis angular velocity was low in males, the high upper torso angular velocity seems indicating both good angular momentum transferred up from the pelvis, and strong contribution from abdominal oblique. But considering the numbers in previous studies, it is questionable if these differences in trunk rotation velocities are real gender difference, as these values are all still in the range that males have performed.

At the Instant of Throwing Shoulder Maximum External Rotation (MER)

The maximum angle of shoulder external rotation is essential as it is both a good predictor of good ball velocity (Matsuo et al., 2001) and an indicator of potential shoulder injury (Fleisig et al., 1995). However, unlike the expectations, neither the shoulder external rotation nor other variables describing throwing arm kinematics reached significance at this instant. The reason that I hypothesized less shoulder external rotation in females was due to the less upper torso angular velocity in the COC-phase, which did not really occur. Therefore, this variable plays no role explaining the different ball velocities displayed between genders.

During the Arm Acceleration (ACC) and Arm Deceleration (DEC) phase

Although the initiation of the ACC-phase is marked by the beginning of shoulder internal rotation, the most critical variable in this phase is the maximum elbow extension angular velocity. In the current study, females were found to have significantly lower magnitude of this variable, in agreement with the finding of Atwater (1970). While elbow is distal to shoulder spatially, it is proximal to shoulder temporally in the kinetic chain. Throwing elbow starts to extend prior to throwing shoulder starts to internally rotate (Fleisig, Barrentine et al., 1996), which means the initiation of elbow extension does not only passively rely on the energy passed up sequentially through the body, but needs elbow extensors to contribute to. Further evidence includes that fact that baseball pitchers with triceps paralyzed could only generate 80% of the original ball velocity (Fleisig, Barrentine et al., 1996). Triceps was found highly activated to overcome the elbow flexion in most of the COC-phase and then accelerate elbow extension (Jobe et al., 1984); therefore, the lower elbow extension angular velocity could be a sign of insufficient triceps strength.

While shoulder internal rotation starts in the ACC-phase, the peak angular velocity of this movement usually occurs in the very beginning of the DEC-phase, that is, after ball release. The reason is probably due to the peak elbow extension at ball release further reduces the moment of inertia of arm to the longitudinal axis. Surprisingly, the peak value of this variable for females, although at the low end comparing to previous male-based studies (Table 2.6), is not significantly different to males'. However, it is probably not the case that both female and male participants in the current study showed low shoulder internal rotation angular velocity. According to Escamilla et al. (2001), baseball pitching researches using manual digitizing and visual identification of joint centers consistently reported lower value in this specific variable, comparing to those researches using automatic tracking of external markers. As those manually-digitized researches were all outdoors, using the same 120Hz cameras, while the automatic-tracked studies generally used 200 or 240Hz cameras indoor, it is not known whether the trend of lower value of this variable was caused by using external markers or lower camera sampling rate. In the current study, one female participant had a peak value of 9,392 $^{o}\bullet s^{-1}$, while one male participant showed an astonishing value of 10,320 $^{o}\bullet s^{-1}$. These values are similar to the maximum value of 9,198 $^{o}\bullet s^{-1}$ according to also manually-digitized data by Pappas et al. (1985), performed by a professional pitcher. It seems that elite female baseball pitchers could have comparable shoulder internal rotation angular velocity to elite male baseball pitchers.

At the Instant of Ball Release (REL)

Although it is already the final instant that a pitcher can hold the ball, this event is still critical, as several variables at this instant are results of performances during previous phases, or related to ball velocity. For example, the less trunk lateral tilt for females, although marginally failed to reach statistical significance, may be a result of less contribution and lack of strength of abdominal muscles during the COC-phase, predicted by less upper torso/pelvis separation angle at the SFC. Moreover, pitchers with higher ball velocity exhibited more trunk forward tilt (Escamilla et al., 2002; Matsuo et al., 2001). The weaker abdominal muscles may also explain the more upright trunk of females comparing to previously reported values of males (Table 2.8), although the difference was not statistically significant as hypothesized. Females also rotated their pelvis more than males. as reported by Atwater (1970). In contrast, the angle that the upper torso traveled was not significantly different between both genders. These results contradict to Ito et al. (2005), in which female baseball pitchers showed less upper torso angle rotated.

Besides the trunk forward tilt, the stride knee extension was found important to give a final burst of ball velocity, as it is a sign that the stride leg can stop and brace the body, converting the linear momentum of the body during the ST-phase into angular momentum that facilitating the trunk tilts forward (Matsuo et al., 2001). In the current study, the knee flexion angle at the REL for females was not only higher comparing to males as hypothesized (Table 4.4), but also higher than the same variable for females at the SFC (Table 4.2). In fact, eight of eleven female pitchers flexed their stride knee throughout the pitching, instead of extending it. Females also displayed much lower knee extension angular velocity than males, as expected. Moreover, while all male participants were extending their stride knee, four of the eleven female pitchers are, in fact, flexing their stride knee at the REL. While it is not possible to completely rule out the probability that female pitchers were instructed to flex their knee during pitching, it is very unlikely and can be explained by no reason. Therefore, the stride knee flexion throughout the COC and ACC-phase and less knee extension angular velocity in females should suggest that the stride leg may not strong enough to firmly stop and brace the body.

Summary and Further Discussion of Kinematics

Overall, kinematic differences between female and male elite baseball pitchers are limited. The most obvious differences are for the lower body and the trunk at the SFC, and these differences are most likely inherited from the differently performed BAL instant and ST-phase. Most differences found after SFC are probably not real differences between genders, as the females' values are, in fact, comparable to males in many previous studies. The only differences that are probably meaningful are the slower elbow extension, the stride knee flexion, and the limited knee extension angular velocity in females.

Moreover, these variables can be categorized in to two types. Baseball pitching involves a kinetic chain from the ground up; the lower body, trunk, and the knee kinematics are at the early or proximal end of the kinetic chain, while the rapid elbow extension is at the late or distal end of the chain. The late or distal elements performances of the chain are constrained by the early or proximal end elements executions. While the kinematics for females that occur earlier than elbow extension, such as pelvis and upper torso rotation angular velocities and shoulder external rotation angle are all performed normally and are comparable to males, the still-low elbow extension angular velocity could be an essential difference between genders. The late occurrence and its very-rapid nature make a pitcher have very little control on this variable. In contrast, the lower body and trunk mechanics are more possible to be adjusted, as they are among the initiation of throwing and not that rapid. Some neuromuscular controls may involve and makes them strategic results, with or without awareness of the pitchers. For these variables, although the current evidence shows statistically significant differences between genders, it is still not clear if these differences really represent a general picture.

It is not surprising that many kinematic differences can be explained by strength differences between genders. Kinetic analyses suggest the net linear and rotational loads acting at females' shoulder and elbow are 50% and 60% comparing to males, respectively. Assuming similar agonist/antagonist firing relationship between genders, forces and torques that females' musculatures generate are also proportional lower. It also should not be ignored that although participants were selected to represent elite amateur pitchers in both genders, female pitchers are real "amateur" and train themselves as Sunday baseball players, while those male college or semi-pro players should have experienced some near-professional training in both facilities and schedules. For example, according to NCAA regulations, a college baseball player can play or practice for up to 20 hours during season (*2006-07 NCAA Division I Manual: Constitution, Operating Bylaws, and Administrative Bylaws*, 2006, p. 247), but this amount of training is not possible to those females as they do not take baseball as one of their career choices. With unequal training, the difference in muscle strength between female and male baseball pitchers should be even larger than those numbers reported in researches comparing elite swimmers or weight lifters of different genders.

Nevertheless, the kinematic difference may not be completely explained by strength. In a research comparing kinematic and kinetic among pitchers from different development stages (Fleisig et al., 1999), the youth pitchers group had similar body height (167±9 cm), ball velocity (28±1 m•s^{-1}) and kinetic (Table 2.10) to female pitchers in the current study (169.5±8.4 cm, 26.8±1.5 m•s^{-1}), while their professional pitchers' height (187±8 cm), ball velocity (37±2 m•s^{-1}) and kinetic were similar to current male participants (187.5±9.1 cm, 36.3±1.8 m•s^{-1}). Surprisingly, while the relation of body height and muscle strength between youth and adult professional pitchers should be similar to it between female and male pitchers, none of kinematic and temporal differences found between genders in the current study was found between the youth and professional group in that research. In fact, youth and adult pitchers were found extremely similar in kinematic and timings that virtually no difference exists. On the other hand, some variable that probably relative to lower force-resistance ratio during throwing, such as higher shoulder horizontal adduction and elbow flexion (Fleisig, Escamilla, Andrews et al., 1996), were not found in the current study. It seems like there is something else that contributes to the kinematic and temporal difference, and therefore, performance difference in ball velocity, between genders.

Structural differences such as higher knee valgus angle for females were suspected to contribute to some kinematic features. Such kinds of differences between genders, however, are general ideas instead of consistent facts, and must be applied carefully, as sometimes the individual difference may be larger than gender gap. While the valgus angle was neither statically measured nor dynamically calculated, it is not appropriate to make any conclusion regarding this issue. It should also be noticed that dynamic knee valgus angle may also involve hip abduction and ankle eversion (Hewett et al., 2005), indicating that the difference is not purely structural, but also involves some neuromuscular controls.

Temporal Differences between Genders

Although female baseball pitchers may be kinematically similar to their male counterparts, this conclusion is based on discrete kinematic values at certain checkpoints and some peak values. If those kinematic variables look good separately but not coordinated well in time frame, they may not contribute to some expected results such as high ball velocity (Matsuo et al., 2001). Therefore, temporal variables must be also inspected.

For timings, only the timing of max knee extension angular velocity is really different between genders. Females peak their stride knee extension angular velocity later than males, and this peak value, in average, occur even after the ball release. Considering it with the fact that females flex their knee throughout the COC and ACC phases and have much lower knee extension angular velocity at the REL, it seems females utilize their stride leg the most after they throw the ball to regain their balance, not to bracing their body to facilitate pitching. That is, this difference is not really a timing issue but a kinematical flex-or-extend issue.

In summary, female baseball pitchers definitely have similar timing pattern to males, as hypothesized; although it looks like females reach max shoulder external rotation earlier, and peak the angular velocities of shoulder internal rotation or probably also elbow extension later, comparing to males in current and previous studies (Table 2.11 and 2.12). Figure 5.1 plots the angular velocities of different body segments against REL_T, performed by one female participant. In this figure, it is clear that how the body segments sequentially peak their angular velocities to achieve final high ball velocity (Takahashi et al., 2002a).

However, in agreement with hypothesis, female spend significantly longer time to accomplish the pitching process, defined from SFC to REL. The current males' number is similar to most previous studies, indicating the longer time that females spend could be a critical difference between genders. Although relative timings of females are very similar to males, absolute time passed between selected temporal events is, therefore, longer in females.

This fact reveals many hidden kinematical differences that could not have been noticed with those described variables. For example, considering longer time used but similar angle traveled, it is not surprising that the average angular velocity of upper trunk or even pelvis in females would be significantly lower than males, as reported by Ito et al. (2005), which was found related to slower ball velocity (Stodden et al., 2001). Moreover, while angular velocity equals to the product of angular acceleration and time, the comparable kinematic numbers and longer time spent indicate less acceleration in females. That is, while the peak angular velocity may be similar between genders, females take longer time to accelerate their segments to reach that peak. As also depicted in Atwater (1970), on a velocity-time plot, the slope in females should not be as steep as in males.

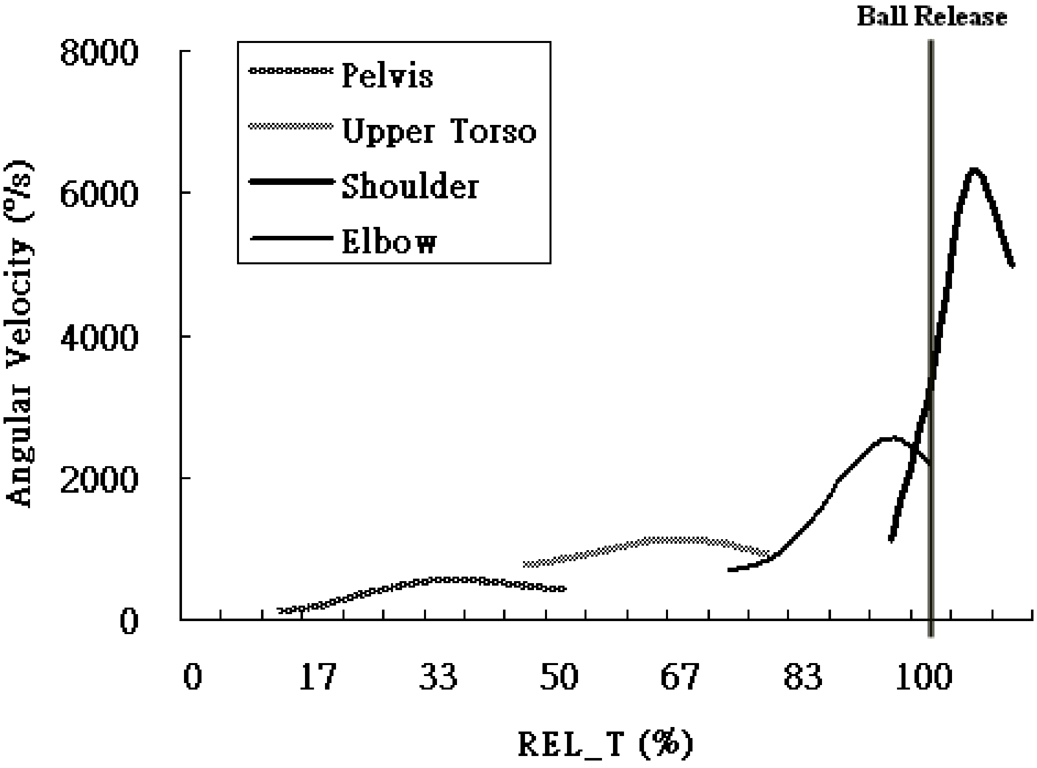


Figure 5.1 An example of sequential peaking of angular velocities

Performance Difference in Ball Velocity

The performance of a pitcher can be evaluated with ball velocity, accuracy, and movement. However, although accuracy and movement could be scored based on visual observation by professional scouts, they are hard to be objectively measured. Therefore, ball velocity is the most practical way to quantitatively evaluate pitching performance. Two-sample K-S test shows that the ball velocity in females is significantly lower than males (Table 3.1). Interestingly, the average female-male performance ratio in ball velocity was 0.74, very similar to the ratio of current javelin throw world record between genders of 0.73 ("International Association of Athletics Federations Records,"). With the kinematical and temporal similarities presented, what factors really cause this difference? Many factors may play a role. Some of them could be explained by the current study, while others need further research to answer.

While the strength differences mentioned before definitely should be part of the answer, the body size; or body height, to me more specific, is another important factor. Peak angular velocities in females are generally comparable to males; however, ball velocity is decided by tangent velocity of throwing hand. Females are significantly shorter than males (Table 3.1), and the arm length of females should be proportionally shorter, too. As linear velocity of the distal end of a segment is the product of angular velocity and segment length, with shorter arm, the distal linear velocity in females can not be as fast as males, even if given similar angular velocity.

The kinematic differences found, although very limited, could still give some disadvantage in generating high ball velocity to females. First, females may lift their stride knee lower than males, storing less potential energy and may lead to slower stride. At the instant of SFC, more open foot placement for females limits the trunk rotation, and less upper torso/pelvis separation decreases the velocity additive effect of energy transfer. Short stride length in females also indicates a slow and weak stride that generates less kinetic energy to be utilized, and suggests that too much knee flexion after the SFC absorbing too much kinetic energy, which also leads to less efficient energy utilization. As consequently presented, that lack of stride knee extension in females means too much energy is absorbed instead of transferring up to facilitate trunk down and forward. Low and late knee extension angular velocity also suggests less help from lower body. Although I did not find trunk forward tilt significantly different between genders, the average females' values are at very low end, while male's values are comparable to most previous researches. Finally, the lower elbow extension angular velocity indicates lower tangent velocity at throwing hand. The timing differences could be another reason. Although not significant, females tend to peak their angular velocities in trunk forward tilt, shoulder internal rotation, and elbow extension later than males, which are all features occurred in pitchers with slower ball velocity (Matsuo et al., 2001).

Finally, while both groups should have represented the samples drafted from the population of the best amateur pitchers available in each gender, the participation bases of females and males are very different. For example, while 470,671 high school boys participated in baseball varsity baseball in 2005-06 academic year, only 1,382 high school girls did so. Moreover, while 15,290 programs provided chance for boys playing high school varsity baseball, only 94 programs opened for girls ("2005-06 High School Athletics Participation Survey," 2006). With such a huge gap of participation, the sampling from best athletes in each gender can be biased. At this moment, this sampling bias still can not be fixed, and should be considered as a limitation of the current study.

The “Throwing Like a Girl” Myth

Overall, the results of the current study are strongly against the long-time “throwing like a girl” myth. It had been believed that females can hardly develop a mature throwing form, and their throwing performance should be, therefore, much inferior to males. The difference of throwing pattern between genders had been noticed by scientists for 70 years (Wild, 1938). While performance gaps between genders in many motor tasks are not obvious before puberty, it seems the gaps in throwing performance, such as ball velocity and throwing distance, between genders exist in early childhood. Seils (1951) tested children of two genders with similar age, body height, and body weight. Among seven categories of motor tasks tested, only throwing performance was clearly different between genders. A meta analysis involved results from more than 30,000 participants further confirmed that boys outperform girls in throwing for 1.5 standard deviations since three years-old, while for other motor tasks, virtually no difference could be observed in performance before 12 (Thomas & French, 1985).

Some researchers developed a scale-rating system to evaluate the maturity of throwing pattern by qualitative observation. They conclude that girls are three to five years behind boys in development of mature throwing pattern, and the differences are mainly of foot stepping and trunk rotation, such as no stride or ipsilateral stride, and no trunk rotation or blocked rotation (Halverson, Roberton, & Langendorfer, 1982; Nelson, Thomas, & Nelson, 1991). Their results of observation and the validity of this rating scale were then quantitatively verified using 3-D biomechanical analysis (Stodden et al., 2006a, 2006b).

Different trunk rotation patterns were also found later in biomechanical studies involved college female athletes (Atwater, 1970) or even baseball pitchers (Ito et al., 2005), implying trunk rotation pattern in throwing could be a real gender difference. However, these researches were either old or only focused on limited kinematic variables. Although stepping and trunk rotation differences are also noticed significant in the current study, they are not only in smaller degrees comparing to those reported before, but in fact are so minor that can not change the general picture that female pitchers pitch very similar to males. After all, low upper torso/pelvis orientation means only less utilization of sequential trunk rotation; not a blocked rotation or no rotation at all. Moreover, while significant differences detected, many female participants performed their stepping and trunk rotation just as good as the best male pitchers, indicating these differences could be overcome. To be more specific, individual difference may be larger than gender difference. Biomechanical research regarding other overhand-throwing task such as tennis serve also support the fact of virtually no kinematic difference between genders (Fleisig, Nicholls, Elliott, & Escamilla, 2003). Meta analysis also suggested throwing mechanics in girls can be improved with training, also performance might not improve simultaneously (Thomas, Michael, & Gallagher, 1994). It is clear that with proper training, females are fully capable of throwing in a form as mature as males.

Summary of Discussion

Kinematic, temporal, and kinetic differences found between genders were discussed with supporting data previously reported. Most kinematic differences are sequentially connected. That is, differences at the REL could be traced back to other differences at the SFC, or even at the BAL. Strength and structural differences between genders may contribute to different kinematics. Some kinematic differences are proximal and early in the kinetic chain and could be modified.

Females have very similar timing pattern in pitching comparing to males, but the absolute time females spent is longer. This can be connected to lower strength, and is supported with kinetic data. Joint loads of females are significantly lower than males, and are comparable to youth male pitchers. In spite of lower joint load, the risk of injury in females should not be overlooked. Regulations set to protect youth pitchers should also be applied to females.

Ball velocity is different between genders, and this difference can attribute to different strength, body height, kinematic, and sampling bias. Among these factors, body height does not completely explain the difference, and other factors are reasonable guess but lack of data to confirm.

With increasing participation of female baseball, more talented or bigger sized women will involve. Female baseball may not only for recreation but becomes more challenging, involving more intense training that would further decrease the difference of strength between pitchers of each gender. The performance gap is therefore expected to shorten, although may not disappear.

CHAPTER 6

CONCLUSIONS

Female participation in baseball has been increasing, and biomechanic analyses specific to females are necessary. The current study is probably the first one investigating the pitching biomechanics of female baseball pitchers. I expected the current study can encourage more females to participate in baseball, and perform pitching safely and excellently.

Summary of the Current Study

Several kinematic hypotheses regarding female baseball pitching were found true, such as less upper torso/pelvis separation, shorter stride, and more stride open foot placement at the SFC; more stride knee flexion, slower knee extension angular velocity, less trunk lateral tilt, and probably more upright trunk at the REL. Other hypothesis were probably not true, such as more open pelvis and foot orientation at the SFC and less maximum shoulder external rotation. The hypotheses of similar timing pattern, longer absolute time spent, and lower joint loads were confirmed. Performance gap in ball velocity was also found between genders, as hypothesized.

Based on the results of the current study, elite female pitchers pitch baseball with comparable kinematic and timings to elite male pitchers. Actually, females performed impressively well, as their peak shoulder internal rotation angular velocity, known one of the most rapid human movements, is not different to males. Performance gap in ball velocity might be not avoided given generally smaller body size of females, although increasing participation base and organized training will shorten this gap to some degrees. Also, it is not only unfair to compare absolute ball velocity between genders, but also unnecessary, as elite males and females are separated in competition baseball, just like in other sports. Moreover, unlike other sports such as javelin, the success of pitching does not only rely on ball velocity. There is no reason that females can not enjoy the same success in baseball pitching like they already have done in many sports.

Moreover, with the current competition level in female baseball, the risk of injury related to pitching should be minimal, based on joints loads calculated. As the elite female pitchers generally compete in recreational baseball events, it should be safe to encourage more women or girls to participate in these activities. As participation is limited, no epidemiology research provides the safety guidelines for pitching amount. It is better to follow the guidelines for youth pitchers until future researches are able to provide female specific information. However, with more participation, female baseball may gradually develop into an official competition that is widely accepted in regional, national, and international events. As the competition level increases, the risk of injury regarding female baseball pitching must be carefully re-evaluated. For example, the more open foot placement, which may not be a threat to females' throwing shoulders with current competition level, needs to be fixed when competitions get more challenging. Similarly, with generally shorter arm length, females need higher angular velocity to reach a certain ball velocity, but more rapid movement of joints may increase the injury risks. This is the same idea behind the anecdotal preference of drafting taller pitchers in professional baseball; that is, given two pitchers with similar ball velocities, baseball scouts would believe that the shorter one is more prone to injury.

Recommendations for Future Studies

The current study serves as a very first step to understand the kinematic and kinetic features of female baseball pitching, with many research questions left to be explored. Future researches may include biomechanical analyses that involve more female participants to perform more trials, to confirm the existence of female-specific kinematic features found in the current study. Indoor data collection with more cameras, higher sampling rate, and external markers are preferred to provide more accurate and precise data. Kinematics regarding lower body and before the SFC, although not emphasized in previous male-based studies, should be also stressed, probably with GRF variables involved. It would be great if body composition data can be measured in combination of biomechanical analysis, serving the role of normalizers instead of just body height or weight, as difference in throwing velocity between genders can be largely explained by fat-free body mass (Van den Tillar & Ettema, 2004). Surface EMG analysis regarding the agonist/antagonist activities, for example, the triceps and the biceps firing patterns during the COC and ACC phases, may be valuable, as females were found firing these muscles differently in rapid elbow flexion task (Ives, Kroll, & Bultman, 1993). Similar approach can be applied to abdominal muscles for the different upper torso/pelvis separation issue.

REFERENCES

2005-06 High School Athletics Participation Survey. (2006). Retrieved December 20, 2006, from http://www.nfhs.org/core/contentmanager/uploads/2005_06NFHSparticipationsurvey.pdf

2006-07 NCAA Division I Manual: Constitution, Operating Bylaws, and Administrative Bylaws. (2006). Indianapolis, IN: The National Collegiate Athletic Association.

2007 Official Rules of Major League Baseball. (2006). Chicago, IL: Triumph Books.

Aguinaldo, A., Buttermore, J., & Chambers, H. (2004). *Sequential body motion and shoulder joint torque between baseball pitchers of various levels.* Paper presented at the Gait and Clinical Movement Analysis Society Meeting, Lexington, KY, USA.

Atwater, A. E. (1970). *Movement characteristics of the overarm throw: A kinematic analysis of men and women performers.* Unpublished doctoral dissertation, University of Wisconsin.

Barrentine, S. W., Takada, Y., Fleisig, G. S., Zheng, N., & Andrews, J. R. (1997). *Kinematic and EMG changes in baseball pitching during a simulated game.* Paper presented at the 21st Annual Meeting of the American Society of Biomechanics, Clemson University, South Carolina, United States.

Beasley, L., Faryniarz, D. A., & Hannafin, J. A. (2000). Multidirectional instability of the shoulder in the female athlete. *Clinics in Sports Medicine, 19*(2), 331-349.

Berlage, G. I. (1994). *Women in Baseball: The Forgotten History*. Westport, CT: Preager.

Borsa, P. A., Dover, G. C., Wilk, K. E., & Reinold, M. M. (2006). Glenohumeral range of motion and stiffness in professional baseball pitchers. *Medicine & Science in Sports & Exercise, 38*(1), 21-26.

Borsa, P. A., Wilk, K. E., Jacobson, J. A., Scibek, J. S., Reinold, M. M., & Andrews, J. R. (2005). Correlation of range of motion and glenohumeral translation in professional baseball pitchers. *The American Journal of Sports Medicine, 33*(9), 1392-1399.

Braatz, J. H., & Gogia, P. P. (1987). The mechanics of pitching. *The Journal of Orthopaedic and Sports Physical Therapy, 9*, 56-69.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale, NJ: Lawrence Earlbaum Associates.

Dillman, C. J., Fleisig, G. S., & Andrews, J. R. (1993). Biomechanics of pitching with emphasis upon shoulder kinematics. *The Journal of Orthopaedic and Sports Physical Therapy, 18*(2), 402-408.

Dun, S., Flesig, G. S., Loftice, J., Kingsley, D., & Andrews, J. R. (2007). The relationship between age and baseball pitching kinematics in professional baseball pitchers. *Journal of Biomechanics*, *40*, 265-270.

Elliott, B., Grove, J. R., & Gibson, B. (1988). Timing of the lower limb drive and throwing limb movement in baseball pitching. *International Journal of Sport Biomechanics, 4*, 59-67.

Elliott, B., Grove, J. R., Gibson, B., & Thurston, B. (1986). A three-dimensional cinematographic analysis of the fastball and curveball pitches in baseball. *International Journal of Sport Biomechanics, 2*, 20-28.

Escamilla, R. F., Fleisig, G., Barrentine, S., Andrews, J., & Moorman, C. (2002). Kinematic and kinetic comparisons between American and Korean professional baseball pitchers. *Sports Biomechanics, 1*(2), 213-228.

Escamilla, R. F., Fleisig, G. S., Barrentine, S. W., Zheng, N., & Andrews, J. R. (1998). Kinematic comparisons of throwing different types of baseball pitches. *Journal of Applied Biomechanics, 14*, 1-23.

Escamilla, R. F., Fleisig, G. S., Zheng, N., Barrentine, S. W., & Andrews, J. R. (2001). Kinematic comparisons of 1996 Olympic baseball pitchers. *Journal of Sports Sciences, 19*(9), 665-676.

Feltner, M. (1989). Three-dimensional interactions in a two-segment kinetic chain. Part II: Application to the throwing arm in baseball pitching. *International Journal of Sport Biomechanics, 5*, 420-450.

Feltner, M., & Dapena, J. (1986). Dynamics of the shoulder and elbow joints of the throwing arm during a baseball pitch. *International Journal of Sport Biomechanics, 2*, 235-259.

Fleisig, G. S. (1994). *The biomechanics of baseball pitching.* Unpublished doctoral dissertation, University of Alabama at Birmingham.

Fleisig, G. S., Andrews, J. R., Dillman, C. J., & Escamilla, R. F. (1995). Kinetics of baseball pitching with implications about injury mechanisms. *The American Journal of Sports Medicine, 23*(2), 233-239.

Fleisig, G. S., Barrentine, S. W., Escamilla, R. F., & Andrews, J. R. (1996). Biomechanics of overhand throwing with implications for injuries. *Sports Medicine, 21*(6), 421-437.

Fleisig, G. S., Barrentine, S. W., Zheng, N., Escamilla, R. F., & Andrews, J. R. (1999). Kinematic and kinetic comparison of baseball pitching among various levels of development. *Journal of Biomechanics, 32*, 1371-1375.

Fleisig, G. S., Escamilla, R. F., Andrews, J. R., Matsuo, T., Satterwhite, Y. E., & W., B. S. (1996). Kinematic and kinetic comparison between baseball pitching and football passing. *Journal of Applied Biomechanics, 12*, 207-224.

Fleisig, G. S., Escamilla, R. F., Barrentine, S. W., Zheng, N., & Andrews, J. R. (1996). *Kinematic and kinetic comparison of baseball pitching from a mound and throwing from flat ground.* Paper presented at the 20th Annual Meeting of the American Society of Biomechanics, Atlanta, Georgia.

Fleisig, G. S., Nicholls, R., Elliott, B., & Escamilla, R. (2003). Kinematics used by world class tennis players to produce high-velocity serves. *Sports Biomechanics, 2*(1), 51-64.

Fleisig, G. S., Zheng, N., Barrentine, S. W., Escamilla, R. F., Andrews, J. R., & Lemak, L. J. (1996). *Kinematic and kinetic comparison of full-effort and partial-effort baseball pitching.* Paper presented at the 20th Annual Meeting of the American Society of Biomechanics, Atlanta, Georgia.

Gowan, I. D., Jobe, F. W., Tibone, J. E., Perry, J., & Moynes, D. R. (1987). A comparative electromyographic analysis of the shoulder during pitching. Professional versus amateur pitchers. *American Journal of Sports Medicine, 15*(6), 586-590.

Halverson, L. E., Roberton, M. A., & Langendorfer, S. (1982). Development of the overarm throw: movement and ball velocity changes by seventh grade. *Research Quarterly for Exercise and Sport, 53*(3), 198-205.

Herring, R. M., & Chapman, A. E. (1992). Effects of changes in segmental values and timing of both torque and torque reversal in simulated throws. *Journal of Biomechanics, 25*, 1173-1184.

Hewett, T. E., Myer, G. D., Ford, K. R., Heidt Jr., R. S., Colosimo, A. J., McLean, S. G., et al. (2005). Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: A prospective study. *The American Journal of Sports Medicine, 33*(4), 492-501.

Hunter, L. Y. (1984). Women's athletics: The orthopedic surgeon's viewpoint. *Clinics in Sports Medicine, 3*(4), 809-827.

International Association of Athletics Federations Records. (2006). Retrieved March 16, 2007, from http://www.iaaf.org/statistics/records/index.html

Ishida, K., & Hirano, Y. (2004). Effects of non-throwing arm on trunk and throwing arm movement in baseball pitching. *International Journal of Sport and Health Sciences, 2*, 119-128.

Ito, H., Nakazato, K., Watarai, K., & Nakajima, H. (2005). Characteristics of trunk rotation movement during the throwing motion in female baseball players. *Medicine & Science in Sports & Exercise, 37*(5 Supplement), S118-S119.

Ives, J. C., Kroll, W. P., & Bultman, L. L. (1993). Rapid movement kinematic and electromyographic control characteristics in males and females. *Research Quarterly for Exercise and Sport, 64*(3), 274-283.

Iwase, H., & Murata, A. (2001). *Discussion on skillful baseball pitch using three-dimensional cinematographic analysis* -- *Comparison of baseball pitch between skilled and unskilled pitchers.* Paper presented at the 2001 IEEE International Conference on Systems, Man, and Cybernetics.

Jobe, F. W., Moynes, D. R., Tibone, J. E., & Perry, J. (1984). An EMG analysis of the shoulder in pitching: A second report. *The American Journal of Sports Medicine, 12*(3), 218-220.

Jobe, F. W., Tibone, J. E., Perry, J., & Moynes, D. R. (1983). An EMG analysis of the shoulder in throwing and pitching: A preliminary report. *The American Journal of Sports Medicine, 11*(1), 3-5.

Kazai, N., Kumamoto, M., Okamoto, T., Yamashita, N., Goto, Y., & Maruyama, H. (1976). Electromyographic study of the overhand pitching in terms of the functional mechanism of the upper extremity and the shoulder girdle muscles. *Japanese Journal of Physical Education, 21*(3), 137-144.

Logan, G. A., McKinney, W. C., Rowe, W., & Lumpe, J. (1966). Effect of resistance through a throwing range-of-motion on the velocity of a baseball. *Perceptual and Motor Skills, 23*(1), 55-58.

Lyman, S., Fleisig, G. S., Andrews, J. R., & Osinski, E. D. (2002). Effect of pitch type, pitch count, and pitching mechanics on risk of elbow and shoulder pain in youth baseball pitchers. *The American Journal of Sports Medicine, 30*(4), 463-468.

MacWilliams, B. A., Choi, T., Perezous, M. K., Chao, E. Y. S., & McFarland, E. G. (1998). Characteristic ground-reaction forces in baseball pitching. *The American Journal of Sports Medicine*, *26*(1), 66-71.

Matsuo, T. (2001). 動作の客観的評価法の提案. *Annual Report of the Japanese Motor Learning Seminar, 11*, 85-88.

Matsuo, T., Escamilla, R. F., Fleisig, G. S., Barrentine, S. W., & Andrews, J. R. (2001). Comparison of kinematic and temporal parameters between different pitch velocity groups. *Journal of Applied Biomechanics*, *17*, 1-13.

Matsuo, T., Matsumoto, T., Mochizuki, Y., Takada, Y., & Saito, K. (2002). Optimal shoulder abduction angles during baseball pitching from maximal wrist velocity and minimal kinetics viewpoints. *Journal of Applied Biomechanics, 18*(4), 306-320.

Matsuo, T., Takada, Y., Matsumoto, T., & Saito, K. (2000). Biomechanical characteristics of sidearm and underhand baseball pitching: Comparison with those of overhand and three-quarter-hand pitching. *Japanese Journal of Biomechanics in Sports & Exercise 4*(4), 243-252.

Miller, N. R., Shapiro, R., & Mclaurin, T. M. (1980). A technique for obtaining spatial kinematic parameters of segments of biomechanical systems from cinematographic data *Journal of Biomechanics, 13*(7), 535-541.

Morrey, B. F., & An, K. N. (1983). Articular and ligamentous contributions to the stability of the elbow joint. *The American Journal of Sports Medicine*, *11*(5), 315-319.

Mullaney, M. J., McHugh, M. P., Donofrio, T. M., & Nicholas, S. J. (2005). Upper and lower extremity muscle fatigue after a baseball pitching performance. *The American Journal of Sports Medicine, 33*(1), 108-113.

Murata, A. (2001). Shoulder joint movement of the non-throwing arm during baseball pitch--comparison between skilled and unskilled pitchers. *Journal of Biomechanics, 34*, 1643-1647.

Murray, T. A., Cook, T. D., Werner, S. L., Schlegel, T. F., & Hawkins, R. J. (2001). The effects of extended play on professional baseball pitchers. *The American Journal of Sports Medicine, 29*(2), 137-142.

Nelson, K. R., Thomas, J. R., & Nelson, J. K. (1991). Longitudinal change in throwing performance: Gender differences. *Research Quarterly for Exercise and Sport, 62*(1), 105-108.

Olsen, S. J., Fleisig, G. S., Dun, S., Loftice, J., & Andrews, J. R. (2006). Risk factors for shoulder and elbow injuries in adolescent baseball pitchers. *The American Journal of Sports Medicine, 34*, 905-912.

Pappas, A. M., Zawacki, R. M., & Sullivan, T. J. (1985). Biomechanics of baseball pitching: A preliminary report. *The American Journal of Sports Medicine, 13*(4), 216-222.

Petty, D. H., Andrews, J. R., Fleisig, G. S., & Cain, E. L. (2004). Ulnar collateral ligament reconstruction in high school baseball players: clinical results and injury risk factors. *The American Journal of Sports Medicine, 32*(5), 1158-1164.

Regulation and Rule Changes for 2007. (2006). Retrieved November 17, 2006, from http://www.littleleague.org/media/Rule_Changes_09-06.pdf

Riegger-Krugh, C., & LeVeau, B. F. (2002). Biomechanical Considerations. In M. L. Ireland & A. Nattiv (Eds.), *The Female Athlete*. Philadelphia, PA: Saunders.

Russell, K. A., Palmieri, R. M., Zinder, S. M., & Ingersoll, C. D. (2006). Sex differences in valgus knee angle during a single-leg drop jump. *Journal of Athletic Training, 41*(2), 166-171.

Sakurai, S., Ikegami, Y., Okamoto, A., Yabe, K., & Toyoshima, S. (1993). A three-dimensional cinematographic analysis of upper limb movement during fastball and curveball baseball pitches. *Journal of Applied Biomechanics, 9*, 47-65.

Seils, L. G. (1951). The relationship between measures of physical growth and gross motor performance of primary-grade school children. *The Research Quarterly, 22*, 244-260.

Shapiro, R. (1978). Direct linear transformation method for three-dimensional cinematography. *The Research Quarterly, 49*, 197-205.

Sisto, D. J., Jobe, F. W., Moynes, D. R., & Antonelli, D. J. (1987). An electromyographic analysis of the elbow in pitching. *The American Journal of Sports Medicine, 15*(3), 260-263.

Stodden, D. F., Fleisig, G. S., Langendorfer, S. J., & Andrews, J. R. (2006a). Kinematic constraints associated with the acquisition of overarm throwing, Part I: step and trunk actions. *Research Quarterly for Exercise and Sport 77*(4), 417-427.

Stodden, D. F., Fleisig, G. S., Langendorfer, S. J., & Andrews, J. R. (2006b). Kinematic constraints associated with the acquisition of overarm throwing, Part II: upper extremity actions. *Research Quarterly for Exercise and Sport, 77*(4), 428-436.

Stodden, D. F., Fleisig, G. S., McLean, S. P., & Andrews, J. R. (2005). Relationship of biomechanical factors to baseball pitching velocity: within pitcher variation. *Journal of Applied Biomechanics, 21*(1), 44-56.

Stodden, D. F., Fleisig, G. S., McLean, S. P., Lyman, S. L., & Andrews, J. R. (2001). Relationship of pelvis and upper torso kinematics to pitched baseball velocity. *Journal of Applied Biomechanics, 17*, 164-172.

Takahashi, K., Fujii, N., & Ae, M. (2002a). *Kinematic comparison of different pitch velocity groups in baseball using motion model method.* Paper presented at the XXth ISBS Symposium, Caceres, Spain.

Takahashi, K., Fujii, N., & Ae, M. (2002b). *野球のピッチングにおける大きな球速獲得のための動作の違いについて*. Paper presented at the Japanese Society of Biomechanics, Aichi, Japan.

Takahashi, K., Fujii, N., & Ae, M. (2002c). *野球の投球における球速の異なる投手の下肢の動作の違いについて～平均動作モデルを用いて～*. Paper presented at the Japanese Society of Physical Education, Saitama, Japan.

Thomas, J. R., & French, K. E. (1985). Gender differences across age in motor performance: A meta-analysis. *Psychological Bulletin, 98*(2), 260-282.

Thomas, J. R., Michael, D., & Gallagher, J. D. (1994). Effects of training on gender differences in overhand throwing: A brief quantitative literature analysis. *Research Quarterly for Exercise and Sport, 65*(1), 67-71.

Toyoshima, S., Hoshikawa, T., Miyashita, M., & Oguri, T. (1973). *Contribution of the body parts to throwing performance.* Paper presented at the 4th International Seminar on Biomechanics, University Park, PA, United States.

Toyoshima, S., Matsui, H., & Miyashita, M. (1971). An electromyographic study of the upper-arm muscles involved in throwing. *Japanese Journal of Physical Education, 15*(2), 103-110.

Van den Tillar, R., & Ettema, G. (2004). A force-velocity relationship and coordination patterns in overarm throwing. *Journal of Sports Science and Medicine, 3,* 211-219.

Watkins, R. G., Dennis, S., Dillin, W. H., Schnebel, B., Schneiderman, G., Jobe, F. W., et al. (1989). Dynamic EMG analysis of torque transfer in professional baseball pitchers. *Spine, 14*(4), 404-408.

Wells, C. L. (1991). *Women, Sport, & Performance: A Physiological Perspective*. Champaign, IL: Human Kinetics.

Werner, S. L., Fleisig, G. S., Dillman, C. J., & Andrews, J. R. (1993). Biomechanics of the elbow during baseball pitching. *The Journal of Orthopaedic and Sports Physical Therapy, 17*(6), 274-278.

Werner, S. L., Murray, T. A., Hawkins, R. J., & Gill, T. J. (2002). Relationship between throwing mechanics and elbow valgus in professional baseball pitchers. *Journal of Shoulder and Elbow Surgery, 11*, 151-155.

Wight, J., Richards, J., & Hall, S. (2004). Influence of pelvis rotation styles on baseball pitching mechanics. *Sports Biomechanics, 3*(1), 67-84.

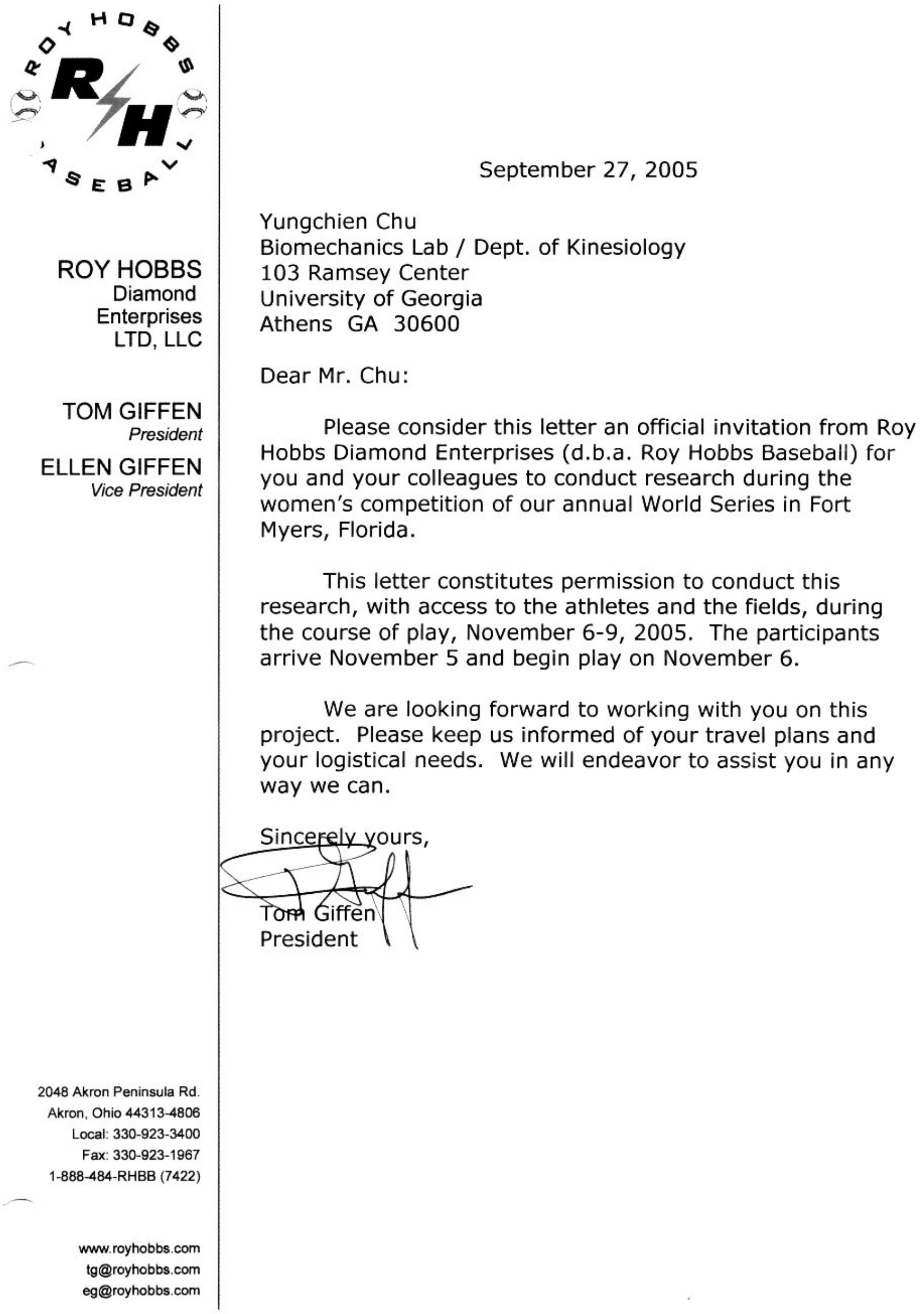
Wild, M. R. (1938). The behavior pattern of throwing and some observations concerning its course of development in children. *Research Quarterly, 9*(3), 20-24.

Women's Baseball World Cup. (2006). Retrieved February 12, 2007, from http://www.baseball.ch/2003/t/wwc/wbwc.htm

Zatsiorsky, V. M. (2002). *Kinetics of Human Motion*. Champaign, IL: Human Kinetics.

APPENDIX A

AUTHORIZATION LETTER FOR VIDEOTAPING THE FEMALE DATA



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September 27, 2005

Yungchien Chu
Biomechanics Lab / Dept. of Kinesiology
103 Ramsey Center
University of Georgia
Athens GA 30600

Dear Mr. Chu:

Please consider this letter an official invitation from Roy Hobbs Diamond Enterprises (d.b.a. Roy Hobbs Baseball) for you and your colleagues to conduct research during the women's competition of our annual World Series in Fort Myers, Florida.

This letter constitutes permission to conduct this research, with access to the athletes and the fields, during the course of play, November 6-9, 2005. The participants arrive November 5 and begin play on November 6.

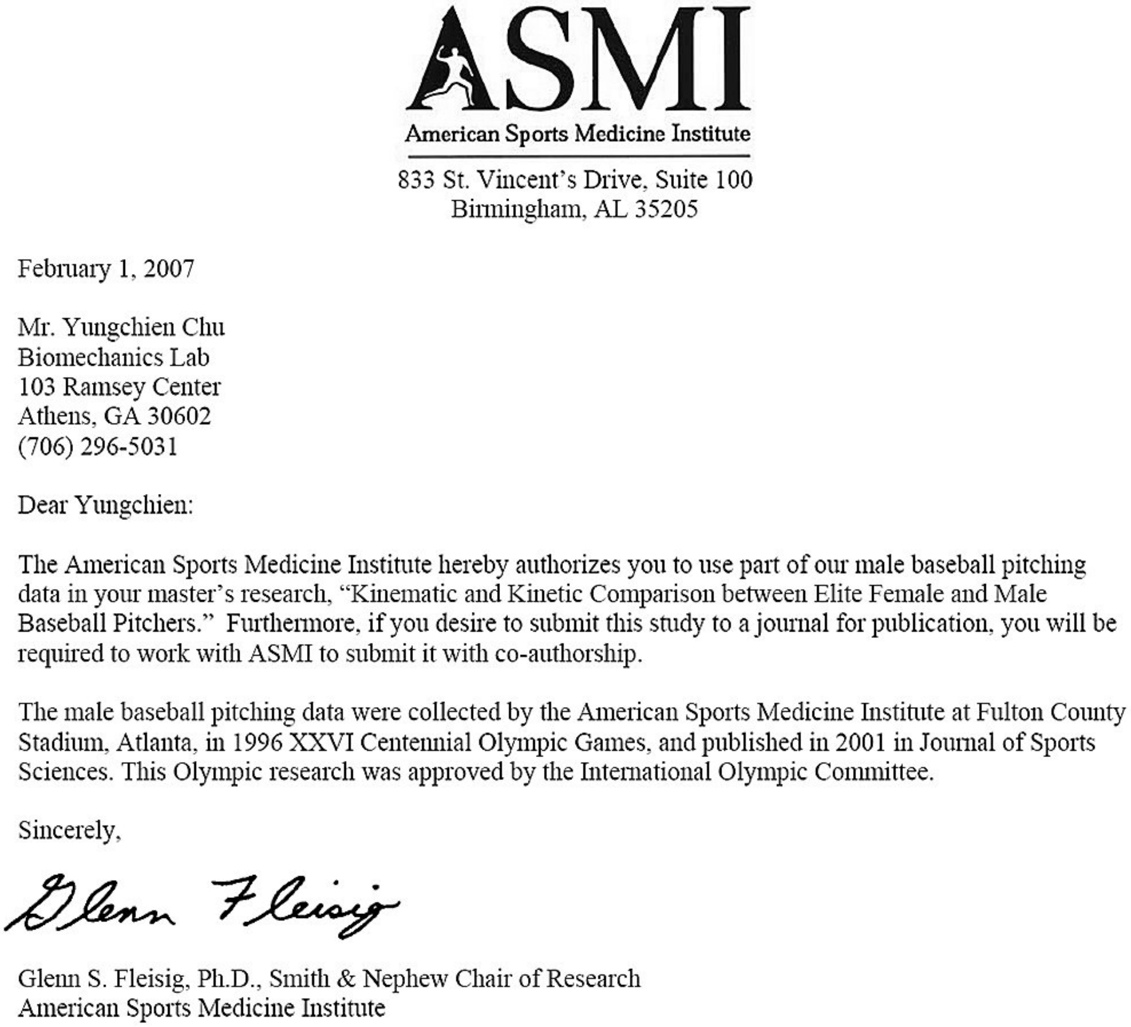
We are looking forward to working with you on this project. Please keep us informed of your travel plans and your logistical needs. We will endeavor to assist you in any way we can.

Sincerely yours,

Tom Giffen
President

APPENDIX B

AUTHORIZATION LETTER FOR USING THE MALE DATA



ASMI
American Sports Medicine Institute
833 St. Vincent's Drive, Suite 100
Birmingham, AL 35205

February 1, 2007

Mr. Yungchien Chu
Biomechanics Lab
103 Ramsey Center
Athens, GA 30602
(706) 296-5031

Dear Yungchien:

The American Sports Medicine Institute hereby authorizes you to use part of our male baseball pitching data in your master's research, "Kinematic and Kinetic Comparison between Elite Female and Male Baseball Pitchers." Furthermore, if you desire to submit this study to a journal for publication, you will be required to work with ASMI to submit it with co-authorship.

The male baseball pitching data were collected by the American Sports Medicine Institute at Fulton County Stadium, Atlanta, in 1996 XXVI Centennial Olympic Games, and published in 2001 in Journal of Sports Sciences. This Olympic research was approved by the International Olympic Committee.

Sincerely,

Glenn Fleisig

Glenn S. Fleisig, Ph.D., Smith & Nephew Chair of Research
American Sports Medicine Institute

APPENDIX C

DETAIL OF THE CUSTOM PROGRAMS USED FOR VARIABLE CALCULATIONS

A custom program was written in MATLAB language to process reconstructed 3-D coordinate data. The program was separated into several subprograms for convenience of modifying and managing. Each subprogram performs one specific function, shown in Table A.1.

Kinematic calculations are based on Fleisig's equations (Fleisig, 1994). The methods defining unit vectors and angles have been described in chapter three. Where the length of calculated angle data series is n, sampling frequency is f (i.e., 120 Hz in the current study), and angle_k represents the kth entry of the data series, angular velocities are calculated using these equations:

For $k = 1$, velocity = $(-\text{angle}_{k+2} + 4\text{angle}_{k+1} – 3\text{angle}_k) / (2 / f)$

For $k = 2$, velocity = $(\text{angle}_{k+1} – \text{angle}_{k-1}) / (2 / f)$

For $k = 3$ to $n-2$, velocity = $(-\text{angle}_{k+2} + 8\text{angle}_{k+1} – 8\text{angle}_{k-1} + \text{angle}_{k-2}) / (12 / f)$

For $k = n-1$, velocity = $(\text{angle}_{k+1} – \text{angle}_{k-1}) / (2 / f)$

For $k = n$, velocity = $(\text{angle}_{k-2} – 4\text{angle}_{k-1} + 3\text{angle}_k) / (2 / f)$

Critical events are decided based on these several rules. SFC is the first frame that resultant linear velocity of leading toe decreases to lower than 1.5 m/s; MER is the frame that throwing shoulder external rotation angle reaches maximal; REL is the first frame that the wrist marker surpasses the elbow marker in global X direction; and MIR is the frame that shoulder external rotation angle reaches minimal.

Table A.1. Subprograms and Functions

Subprogram	Function
For kinematic and temporal analysis	
Unitvectorcalc.m	Calculate unit vectors.
Anglecalc.m	Calculate joint and segment angles.
Velocalc.m	Calculate angular velocities.
Eventcalc.m	Find critical events.
For kinetic analysis	
Accecalc.m	Calculate joint linear accelerations in three directions.
Mandicalc.m	Calculate body segment mass, COM, and inertial properties.
Kinecalc.m	Calculate forces and torques using inverse dynamics.

For kinetics, linear accelerations in global X, Y, and Z directions of throwing shoulder, elbow, and wrist need to be obtained first (Fleisig, 1994). Where the length of 3-D position data series is n, sampling frequency is f (i.e., 120 Hz in the current study), and pos_k represents the kth entry of the data series, accelerations are calculated using these equations:

For k = 1, acceleration = $(-pos_{k+3} + 4pos_{k+2} - 5pos_{k+1} + 2pos_k) / f^2$

For k = 2, acceleration = $(pos_{k+2} - pos_{k+1} + pos_k) / f^2$

For k = 3 to n-2, acceleration = $(-pos_{k+2} + 16pos_{k+1} - 30pos_{k-1} + 16pos_{k-1} - pos_{k-2}) / 12f^2$

For k = n-1, acceleration = $(pos_{k+1} – 2pos_k + pos_{k-1}) / f^2$

For k = n, acceleration = $(pos_{k-3} – 4pos_{k-2} + 5pos_{k-1} - 2pos_k) / f^2$

Segment mass, COM, and moment of inertia are estimated based on participants' body height and weight, using Zatsiorsky's equations (Zatsiorsky, 2002), shown in Table A.2. Calculations of forces and torques are also based on Fleisig (1994).

Table A.2. Coefficients of multiple regression equations for estimating the inertial properties of human body segments*

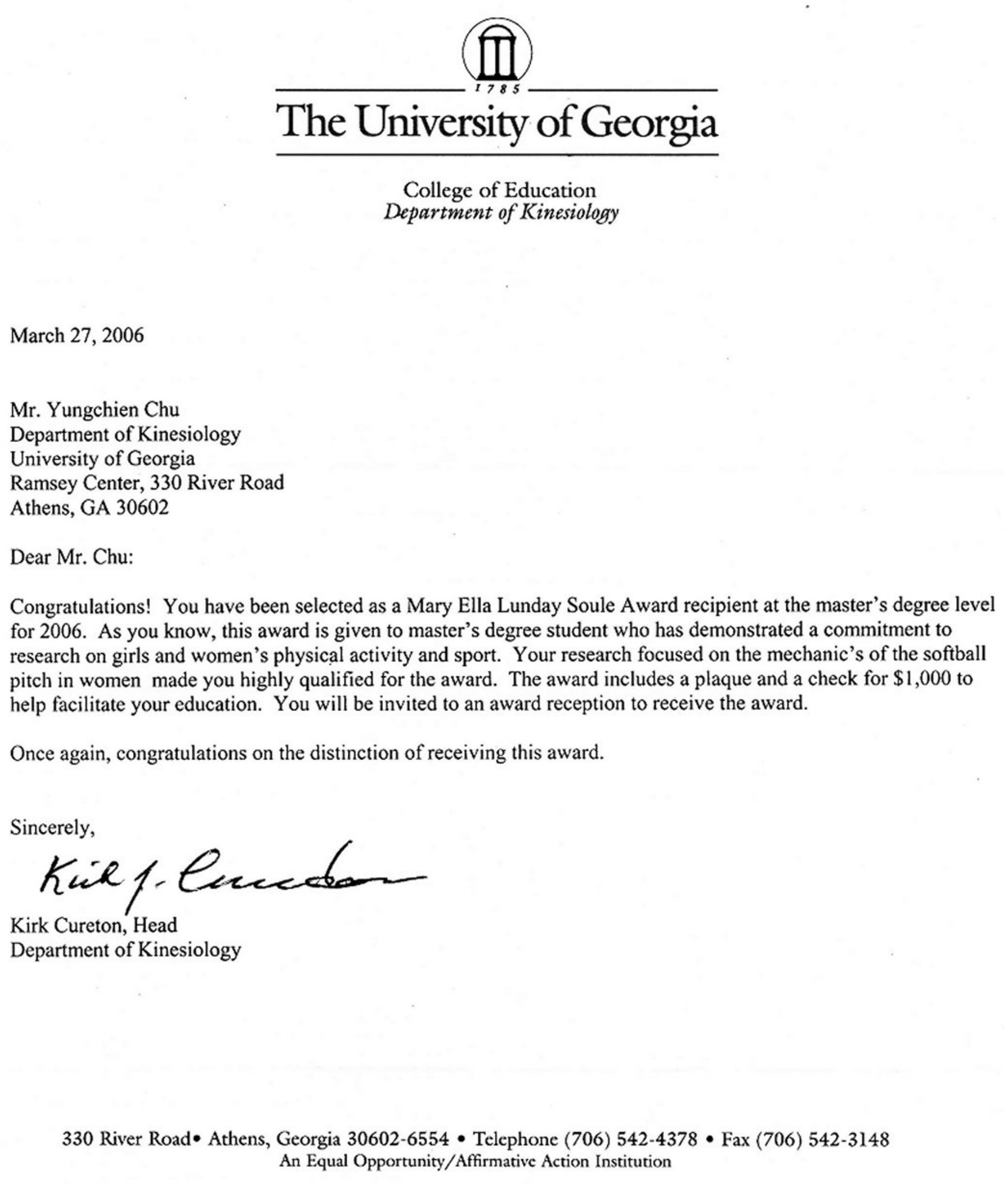
Females	B_0	B_1	B_2
Hand Mass (kg)	-0.116	0.0017	0.002
Forearm Mass (kg)	0.295	0.009	0.0003
Arm Mass (kg)	0.206	0.0053	0.0066
Forearm COM Position (%)**	57.42	--	--
Arm COM Position (%)**	55.99	--	--
Forearm I Longitudinal (kg*cm^2)	7.4	0.21	-0.08
Arm I Longitudinal (kg*cm^2)	-118.6	1.19	0.44
Forearm I Transverse (kg*cm^2)	-138.5	0.533	0.887
Arm I Transverse (kg*cm^2)	-330.4	-0.461	2.67
Males	B_0	B_1	B_2
Hand Mass (kg)	-0.1165	0.0036	0.00175
Forearm Mass (kg)	0.3185	0.01445	-0.00114
Arm Mass (kg)	0.250	0.03012	-0.0027
Forearm COM Position (%)**	57.26	--	--
Arm COM Position (%)**	55.02	--	--
Forearm I Longitudinal (kg*cm^2)	5.66	0.306	-0.088
Arm I Longitudinal (kg*cm^2)	-16.9	0.662	0.0435
Forearm I Transverse (kg*cm^2)	-67.9	0.855	0.376
Arm I Transverse (kg*cm^2)	-232	1.525	1.343

Note. *The equations are in the form $Y = B_0 \pm B_1X_1 \pm B_2X_2$, where X_1 is body weight in kg, X_2 is body height in cm.

** The COM positions are presented in the form of percentage length from the distal end of the segment.

APPENDIX D

WINNING NOTICIFICATION LETTER OF THE 2006 MARY ELLA LUNDAY SOULE AWARD



1785
The University of Georgia

College of Education
Department of Kinesiology

March 27, 2006

Mr. Yungchien Chu
Department of Kinesiology
University of Georgia
Ramsey Center, 330 River Road
Athens, GA 30602

Dear Mr. Chu:

Congratulations! You have been selected as a Mary Ella Lunday Soule Award recipient at the master's degree level for 2006. As you know, this award is given to master's degree student who has demonstrated a commitment to research on girls and women's physical activity and sport. Your research focused on the mechanic's of the softball pitch in women made you highly qualified for the award. The award includes a plaque and a check for $1,000 to help facilitate your education. You will be invited to an award reception to receive the award.

Once again, congratulations on the distinction of receiving this award.

Sincerely,

Kirk J. Cureton

Kirk Cureton, Head
Department of Kinesiology

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